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# PHYSICS OF METEORS

J. Delcourt

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Issy-les-Moulineaux, 22 November 1963

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the study of meteors, it is not necessary to know the details of a meteorite's geometry. The only two parameters involved in the development are:

S, the meteorite instantaneous right angle cross section, which is involved in the evaluation of the friction forces, and more generally, in the study of interactions between the meteorite and the surrounding air; and

M, the mass of the meteorite, which in particular enters in the form of an inertial force in the determination of the meteorite's motion. We have: $M = \delta \cdot V$, where $\delta$ is the density, and V is the volume of the meteorite. We call the following ratio the "shape factor":

$$A = \frac{S}{V^{2/3}} \tag{1}$$

A = 1.2 for a sphere, it varies between 1 and 1.7 for a cube, and for a prism of normal cross section having a side a and a length b, we find:

$$A = \left(\frac{b}{a}\right)^{-2/3}$$

For meteorites of very large dimensions (>1 cm), it can be shown that the meteorites undergo an ablation, which tends to make them spherical in shape (A = 1.2). Generally, we can say that A remains equal to about one.

## 2. Hypothesis on the Structure of the Atmosphere

### 2.1 Density

For a homogeneous and isothermal atmosphere, for which the variations of the acceleration of gravity g with the altitude can be neglected, we can write:

$$\rho(z) = \rho(0)\ e^{-z/H}; \tag{2}$$

where

$$H = \frac{\mathcal{R}T}{\mathcal{M}g} = 29.26\ T \qquad \text{(H in meters and T in } ^{o}\text{K)}$$

being the reference height, $\rho(z)$ the density of air at elevation z, $\mathcal{M}$ the mean molar mass of air, and T the temperature.

The true atmosphere can always be divided into horizontal slices, such that

$$h \leq z < h',$$

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with the slices being taken thin enough to be considered as isothermal. We can then write for the interior of each slice:

$$\rho(z) = \rho(h)\, e^{-\frac{z-h}{H_h}} \tag{3}$$

where,

$$H_h = \frac{\mathcal{R}\, T_h}{\mathcal{M}_h\, g} \tag{4}$$

with $H_h$, $T_h$ and $\mathcal{M}_h$ being the values of H, T and $\mathcal{M}$ in the atmospheric slice considered.

Figure 1 shows the values of $T, \mathcal{M}, \rho$ and H as a function of the altitude z (from ARDC, 1959). $\mathcal{M}$ can be taken as constant in the zone where the meteorite trains form (70 to 120 km altitude).

## 2.2 Mean Free Path

For a population of identical, spherical, and perfectly elastic molecules, whose speeds follow the Maxwell distribution (thermal equilibrium), the mean free path of a molecule is (Refs. 3, 4 and 32):

$$\lambda_o = \frac{1}{\pi\sqrt{2}\cdot N d^2} = \frac{1}{\pi\sqrt{2}\cdot\mathcal{N}}\cdot\frac{\mathcal{M}}{\rho d^2} = \frac{m}{\pi\sqrt{2}\cdot\rho d^2} \approx 27\cdot 10^{-11}\,\frac{\mathcal{M}}{\rho}$$

where: $d = 3.7\cdot 10^{-8}$ cm: mean molecular diameter,

$\mathcal{N} = 6.02\cdot 10^{23}$ molecules per mole, and
$\mathcal{M}$ = mean molecular mass ≈ 28.9

The curve of $\lambda(z)$ (ARDC 1959) is shown in Figure 2.

## 2.3 Thermal Speeds of the Molecules

Let $v_T$ be the root mean square speed of the air molecule in the unperturbed atmosphere. The curve of $v_T(z)$ is shown in Figure 2 (ARDC, 1959). It is seen that, for $z \leq 140$ km, $v_T$ is less than 800 m/sec, approximately. Thus, the thermal velocities of the air molecules are small in comparison with the speeds of most meteorites, at least till the end of their visible train (we shall later see that the speed of a meteorite at the end of its visible train is about 5 km/sec).

## 3. Basic Equations for the Motion of the Meteorite

### 3.1 Deceleration of the Meteorite

Since the thermal velocities of the air molecules can be neglected, it is convenient to treat the problem of the interaction between the meteorite and the surrounding air by considering a counter motion of a beam of air molecules encountering a fixed meteorite.

Let v be the speed of the meteorite, S its right angle cross section, and $\rho$ the density of air. The mass of air which encounters the meteorite during a time $\Delta t$ is:

$$\Delta M' = S\rho v\Delta t.$$

Its momentum is:

$$v\Delta M' = S\rho v^2\Delta t.$$

If a fraction $\Gamma$ of this momentum is imparted to the meteorite, the latter has, after the collision, a momentum $M(v-\Delta v)$, from which the loss of momentum $M\Delta v$ is given by:

$$M\Delta v = \Gamma S\rho v^2\Delta t.$$

From this we obtain the equation for the deceleration of the meteorite:

$$\boxed{M\frac{dv}{dt} = -\Gamma S\rho v^2} \tag{5}$$

$\Gamma$ is called the drag coefficient or coefficient of momentum transfer.

Note that (5) gives the motion of the meteorite while neglecting the acceleration of gravity Mg. This last term is negligible compared with the term $\Gamma S\rho v^2$, for sufficiently small meteorites; i.e., of dimensions less than a millimeter. This is satisfied by most natural meteorites.

### 3.2 Vaporization of the Meteorite

The incident mass of $\Delta M'$ contributes an incident energy:

$$\Delta E = \frac{1}{2} v^2\Delta M' = \frac{1}{2} S\rho v^3\Delta t$$

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Let $\Lambda$ (called the coefficient of energy transfer) be the fraction of this energy which is absorbed by the meteorite. It can be shown (Refs. 1 and 2) that in the first approximation, most of that energy is used for the vaporization of a thin film of the frontal surface of the meteorite. The mass $\Delta M$ of vaporized matter is therefore:

$$\Delta M = \frac{\Lambda}{Q}\,\Delta E = \frac{1}{2}\,\frac{\Lambda}{Q}\,S\rho v^3 \Delta t$$

where Q is the overall heat of vaporization per unit mass of the meteorite. After manipulation, the equation for the decrease of mass by vaporization is obtained:

$$\boxed{\frac{dM}{dt} = -\frac{1}{2}\,\frac{\Lambda}{Q}\,S\rho v^3} \qquad (6)$$

The coefficients $\Gamma$ and $\Lambda$ vary along the trajectory of the meteorite, but their variations are smaller than those of other parameters, such as $\rho$ and v. In the first approximation $\Gamma$ and $\Lambda$ can be considered constant.

## 3.3 Relation Between the Deceleration and the Decrease of Mass

By dividing both sides of (5) and (6), the following relation is obtained:

$$\frac{dM}{M} = \frac{\Lambda}{2\Gamma Q}\,v \cdot dv = \xi v \cdot dv \qquad (7)$$

taking, for the rest of the discussion:

$$\xi = \frac{\Lambda}{2\Gamma Q} \qquad (8)$$

## 4. Reflection of the Air Molecules by the Meteorite

Equations (5), (6) and (7) are very general, and do not imply any hypothesis on the exact mechanisms which lead to the deceleration and vaporization of the meteorite. We shall now examine all these mechanisms.

We shall first study the case where only reflection of the air molecules by the meteorite takes place, with no screening effects present. This means that each molecule of air of the incident beam encounters the meteorite without undergoing any interaction with the other air molecules (contrary to this, the screening effect which we shall study in Section 5 consists of a strong interaction between the molecules of the incident beam and those of the reflected beam).

We shall therefore assume that all the air molecules which encounter the meteorite have a speed v. They are reflected and have, after the collision, a root mean square speed equal to $v_r$.

We call the following quantity the "accommodation coefficient":

$$a = \frac{E_i - E_r}{E_i - E_T}$$

where $E_i$ is the mean kinetic energy of the incident molecules; $E_r$ the mean energy of the reflected molecules; and $E_T$ the mean energy of the of the reflected molecules, for a Maxwellian distribution of speeds corresponding to a surface temperature T of the meteorite. We have:

1) $$E_T << E_i$$

2) $$E_r = \frac{1}{2} m v_r^2 + \mathcal{E}$$

where $v_r$ is the root mean square speed of the reflected molecules; and $\mathcal{E}$ is the dissociation energy, or excitation energy of the reflected molecules.

The mean kinetic energy of the air molecules varies from approximately 15 to 500 ev, when v varies from 10 to 60 km/sec. The study of electric discharges in gases (Refs. 2 and 6) shows that the probability of excitation and ionization of the molecules by impact against a wall remains low for energies of a few hundred electron volts.

Thus we shall take:

$$\mathcal{E} << \frac{1}{2} m v_r^2$$

from which,

$$a \simeq 1 - \left(\frac{v_r}{v}\right)^2$$

where a represents approximately the fraction of kinetic energy lost by the air molecule during the collision.

The energy absorbed by the meteorite is composed of: (1) the stripping energy by impact, and (2) the thermal energy (predominant); heating of the meteorite, fusion, vaporization, boiling.

## 4.1 Laws of Diffused Reflection

Experiments on the impact by molecular or ionic beams on solid targets have shown that these particles undergo a diffuse reflection (scattering). The number of scattered molecules per unit solid angle, in a direction making an angle $\theta$ with the normal to the surface, is proportional to $\cos \theta$. This is the law of Knudsen (Ref. 4), and is analogous to Lambert's law in photometry.

## 4.2 Calculation of the Accommodation Coefficient

The transfer of energy is characterized by the coefficient a, in the absence of the screen, because of the reflected molecules (see Ref. 5). It depends on:

(1) The ratio $m/m'$, where m is the mass of an incident molecule of air and m' is the mass of a molecule of the solid.

(2) The incident kinetic energy: $\frac{1}{2} mv^2$

The atoms at the surface of the solid exert repulsive forces which decrease with distance. In the neighborhood of these atoms, the equipotential surfaces, corresponding to high energies, are roughly spheres which are concentric with the nuclei and have no common point. At greater distances, the equipotential surfaces become one sheet. This sheet becomes a plane when the distance increases.

The collision of low energy particles (for example, particles having thermal speeds of 500 to 100 m/sec) involves only one equipotential surface of one sheet; i.e., one corresponding to the resultant of the repulsive forces from several close atoms. The sum of the masses of those atoms which contribute, during the collision, to the reaction on the incident molecule is generally much greater than the mass of the latter one. In this way, the molecule is reflected (or reemitted) with a weak loss of kinetic energy. On the contrary, however, if the energy of the collision is high (with respect to thermal speeds), the incident particle penetrates further into the atomic lattice. It can be absorbed if its trajectory nears the median plane between the two neighboring atoms. More frequently, the particle is reemitted after having undergone one or several repulsions from the electronic envelopes from one or two atoms of the solid. In this second case, since the mass ratio is much greater, the transfer of energy from the incident molecule to the solid is more important.

In summation, the accommodation coefficient (coefficient of energy transfer in the absence of a screen) "a" depends essentially upon: (1) the atomic mass of the incident particle; (2) the mean mass of an atom from the solid; and (3) the relative speed, which determines the number of atoms, from the solid, which react on the incident particle.

The coefficient a is calculated by treating the problem of collision between particles. In particular, the simple model of the central force and completely elastic collision is attacked in Reference 2. More detailed solutions of other models are found in References 5 and 6. Note that a depends on two other factors: (1) the angle of incidence of the collision, and (2) the surface roughness.

## 4.3 Values for the Accommodation Coefficient

### a) Stony Meteorites

Their composition is a mixture of iron and manganese silicates, iron, aluminum and calcium oxides. The mean atomic mass is of the same order of magnitude as, or perhaps even smaller than, that of air: $m' \lesssim m$. The mean composition of a stony meteorite is given in Table 1 (Ref. 2). The mean atomic mass is deduced for the solid phase; namely, 23. The mean molar mass of air varies from 29 to 26 at an altitude of between 0 and 200 km (ARDC, 1959). From the measurements of Van Voorhis and Compton (Ref. 12) a mean value for a is 0.924 (for $v \simeq 35$ km/sec and normal incidence). Levin (Ref. 1) gives the values:

$$a = 0.96 \text{ for } v = 15 \text{ km/sec}$$
$$a = 0.99 \text{ for } v = 50 \text{ km/sec}$$

In summation, the molecules of air impart all their kinetic energy to the meteor during the collision. The speed of the reemitted particles is relatively low (i.e., of the order of 3 to 6 km/sec) when v varies from 10 to 60 km/sec.

### b) Iron Meteorites

Iron meteorites are composed of iron + nickel, with the percent of nickel varying between 5 and 50 percent, with an average of 9 percent. The atomic mass of iron is 56, and of nickel it is 58.7. This is clearly the case of $m < m'$. Van Voorhis and Compton (Ref. 12) give a = 0.650 (for normal incidence and $v \simeq 35$ km/sec). The values calculated by Levin (Ref. 1) are slightly higher:

for $\mathcal{M} = 29$ (to within 1 percent, from 0 to 120 km) $a = 0.79$
for $\mathcal{M} = 24$ ($z = 250$ km) $a = 0.74$

We shall take an average for a = 0.75.

Thus the air molecules transfer 75 percent of their energy to the iron meteorite. The speed after reflection is half the speed of the incident particle.

## 4.4 Distribution of the Energy

In the absence of a screen, the kinetic energy lost by the air molecule is completely transferred to the meteorite. We therefore have:

$$\boxed{\Lambda = a}$$

## 5. Screen Effect

We say that there is a screen effect if there is a collision interaction between the incident air molecules and those which are reflected by the meteorite. This effect becomes greater as the flux of the incident and reflected molecules becomes more intense. Therefore, the effect increases with: (1) the product $\rho v$, which represents the flux of incident molecules; and (2) the size of the meteorite, which conditions the flux of reflected molecules.

Suppose that a beam of molecules moves toward a meteorite, which for simplification we shall assume to be a circular-plane target. Consider a molecule which is just reflected at a point on this target and located at a distance r from its center. If we suppose that the molecules are reflected according to Knudsen's law (Section 4.1) it can be shown (Ref. 1) that the mean free path $\lambda(r)$ of this reflected molecule, inside the beam of incident molecules, is given by:

$$\lambda(r) = \frac{2}{\pi}\,\lambda(o)\int_0^{\pi/2}\sqrt{1-\left(\frac{r}{R}\right)^2\sin^2\alpha}\cdot d\alpha = \frac{2\lambda(o)}{\pi}\,E\left(\frac{\pi}{2},\frac{r}{R}\right)$$

with

$$\lambda(0) = 2R$$

where R is the radius of the right angle cross section, and $E(\phi, k)$ is an elliptic integral of the second kind. In particular, for $r = R$, $\lambda(R) = 0.64\lambda(0) = 1.28\ R$. The mean value of $\lambda(r)$, as calculated for the whole frontal surface, is

$$\lambda = \frac{16}{3\pi} R \approx 1.7\ R \tag{10}$$

In the first approximation, we can say that a molecule of air reflected by the target and having a speed $v_r$ and a mean free path $\lambda$ remains in front of the target surface during a time:

$$\theta = \frac{\lambda}{v_r} \tag{11}$$

If 1 $cm^2$ of the target surface reflects $N_r$ molecules per second, there are an average of $N_r\theta$ reflected molecules in front of the target. These form a screen, whose total surface area per unit of target surface area is:

$$\Sigma = N_r\theta \cdot \pi d^2$$

where d is the mean molecular diameter ($d \approx 3.7 \cdot 10^{-8}$cm). From (10) and (11):

$$\Sigma = \frac{16}{3} N_r \, d^2 \frac{R}{v_r} \tag{12}$$

The probability that a molecule is not stopped by this screen is:

$$p(N_r) = e^{-\Sigma} \tag{13}$$

This is in fact an approximate evaluation. In reality, the probability that an incident molecule will cross the screen without being stopped by the meteorite (which we shall call the transparency coefficient for the screen, and designate by $\alpha$) is greater than the $p(N_r)$ given by (13). In fact, after a collision in the vicinity of the meteorite the incident molecule can reach the meteorite even though it is deflected from its trajectory, and the reflected molecule can again be reflected back to the meteorite. It can be shown that the transparency coefficient $\alpha$ must have an expression of the form:

$$\alpha = e^{-\beta\Sigma} \tag{14}$$

where $\beta$ is a coefficient less than one.

The number $N_r$ of reflected molecules is given in the steady state regime by:

$$N_r = \alpha N_i = \alpha \frac{\rho v}{m}, \tag{15}$$

where $N = \frac{\rho}{m}$ is the number density of incident molecules in front of the screen. Eliminating $\Sigma$ and $N_r$ from (12), (14) and (15), we get the equation for $\alpha$:

$$\alpha = \exp\left(- \frac{16}{3\sqrt{2\pi}} \beta \frac{R}{\lambda_o} \frac{v}{v_r} \alpha\right) \tag{16}$$

where

$$\lambda_o = \frac{1}{\sqrt{2}\,{}^{1}\pi d^2 N}$$

is the mean free path in free atmosphere. If the transparency $\alpha$ is close to 1, we replace (16) by the approximate equation:

$$1 - \alpha \approx \frac{16}{3\sqrt{2}\pi}\,\beta\,\frac{R}{\lambda_o}\,\frac{v}{v_r} = \frac{16}{3\pi}\,\beta\,\frac{\pi d^2}{m v_r}\,R\rho v \qquad (17)$$

a) Stony Meteorites. Take $\beta = 0.2$ (Ref. 1), $\alpha \sim 1$, $v_r = 3$ km/sec (Ref. 1). We shall admit that the screen effect is negligible if for example $1 - \alpha < 0.1$. For this to be fulfilled, and from (17), we must have:

$$\frac{R}{\lambda_o} < \frac{12 \cdot 10^4}{v} \text{ or } R\rho v < 10^{-3}, \text{ or } z > z_{min}(R).$$

Table 2 gives, as a function of R and v, the altitudes $z_{min}$ above which the screen effect by the reemitted air molecules is negligible[1].

b) Iron Meteorites. The air molecules are reemitted with greater speeds than for stony meteorites. We must therefore expect a weaker screen effect here. From (9) $v_r = v\sqrt{1 - a}$. Equations (16) and (17) become:

$$\alpha = \exp\left(- \frac{16}{3\pi\sqrt{2}}\,\frac{\beta}{\sqrt{1-a}}\,\frac{R}{\lambda_o}\,\alpha\right) \qquad (18)$$

$$1-\alpha \approx \frac{16}{3\pi\sqrt{2}}\,\frac{\beta}{\sqrt{1-a}}\,\frac{R}{\lambda_o} = \frac{16}{3\pi}\,\frac{\beta}{\sqrt{1-a}}\,\frac{\pi d^2}{m}\,R\rho \qquad (19)$$

Take for example $\beta = 0.2$ and $a = 0.75$. To have $1 - \alpha < 0.1$, we must have $(R/\lambda_o) < 0.21$, or $z > z_{min}(R)$. Table 3 gives, as a function of R, the altitudes $z_{min}$ above which the screen effect is negligible ($\lambda_o(z)$ from ARDC, 1959). The altitudes at which the visible meteors make their appearance (in other words the altitudes of the start of vaporization) vary roughly from 80 to 90 km for speeds less than 25 km/sec (region of

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[1] $\lambda_o(z)$ from ARDC, 1959.

low speeds), and from 115 to 125 km for speeds greater than 40 to 45 km/sec (region of high speeds).

Conclusion

The screen resulting from the reemitted air molecules is weak before the start of vaporization for millimetric or lesser stony meteorites; in other words, for most natural meteorites. The results of Section 4 can therefore be applied to these meteorites.

## 6. Sputtering of the Meteorite Molecules by Impact

The sputtering ("arrachement" in French, "Zertstäubung" in German) of the meteorite molecules by impact is a phenomenon which makes its appearance, before vaporization, at the first collisions against air molecules. Each air molecule encountered by the meteorite produces at the surface an intense heating which is very short, and is localized to the close vicinity of the point of impact. A sputtering of the meteorite molecules results. The phenomenon has been studied by analogy with the bombardment of ions on a cathode (Ref. 13).

Let $\nu$ be the mean number of sputtered molecules caused by an incident molecule during the collision, $\varepsilon = a\frac{mv^2}{2}$ the energy transferred to the meteorite by an incident molecule, and $u_o$ the sputtering energy of a molecule ($u_o \simeq 6.10^{-12}$ erg = 4 ev). It was found (Ref. 13) that:

$$\nu = k \left(\frac{\varepsilon}{u_o}\right)^{4/3} \tag{20}$$

where k is a characteristic constant for the material. For iron, $k = 7.10^{-4}$, and for a stony body, $k \simeq 10^{-2}$. For v comprised between 10 and 70 km/sec, we obtain:

$$0.1 < \nu < 10 \quad \text{(stony meteorites)}$$
$$0.004 < \nu < 0.6 \quad \text{(iron meteorites)}$$

By definition, the coefficient of energy transfer by impact sputtering is the ratio:

$$\Lambda_a = E/\varepsilon \tag{21}$$

where E is the secondary energy necessary for the sputtering of the molecule. It can be shown (Ref. 1) that:

$$\Lambda_a = \frac{5}{2} k \left(\frac{\varepsilon}{u_o}\right)^{1/3} = \Lambda_{a,o} v^{2/3} \qquad \text{cgs}$$

For a stony body, $\Lambda_{a,o} \approx 4 \cdot 10^{-6}$, and for iron, $\Lambda_{a,o} = 2.5 \cdot 10^{-7}$. For v comprised between 10 km/sec and 70 km/sec, we have

| | |
|---|---|
| stony body | $4 < \Lambda_a < 14$ percent |
| iron | $0.3 < \Lambda_a < 1$ percent |

Therefore, the total sputtering energy E always remains small as compared with the collision energy $\varepsilon$ transferred to the meteorite. Very low values of $\Lambda_a$ have been observed for various metals.

We can write an equation for the decrease of mass by collision sputtering analogously to (6), with the additional use of the relation $\Lambda = a\alpha$:

$$\frac{dM}{dt} = -\frac{1}{2} \frac{\Lambda \cdot \Lambda_a}{Q_a} \cdot S\rho v^3 = -\frac{1}{2} \alpha \frac{a\Lambda_a}{Q_a} S\rho v^3 = -\frac{1}{2}\alpha \frac{a\Lambda_{a,o}}{Q_a} S\rho v^{11/3} \qquad (22)$$

where $Q_a$ is the specific energy (per gram) of impact sputtering. For iron, $Q_a = 1.8 \cdot 10^{11}$ $erg \cdot g^{-1}$ (Ref. 1). For stony bodies, $Q_a$ is of the same order of magnitude. This is the numerical value which is used for all meteorites.

## 6.1 Numerical Values of the Drag Coefficient $\Gamma$ (taking into account the incident molecules and the molecules reemitted and sputtered by impact)

The mass of air incident on the meteorite has a steady momentum algebraically equal to:

$$\alpha_\Gamma \cdot d\, M' \cdot v$$

where $\alpha$ is the transparency coefficient for momentum transfer. The reemitted air molecules have a momentum whose component along the direction of $\vec{v}$ is:

$$-\, \alpha_N k \cdot dM' v_r$$

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With $\alpha_N$ being the transparency coefficient for the transfer of the number of molecules, and k being a numerical factor related to the space distribution of reemitted or sputtered molecules (scattering law and shape of the surface). The molecules removed from the meteorite have a momentum whose component along the direction of $\vec{v}$ is:

$$- k \cdot dM \cdot v_a ,$$

from which the equation,

$$\Gamma dM'v = \alpha_\Gamma dM'v + \alpha_N k \cdot dM'v_r - k \cdot dM \cdot v_a . \qquad (23)$$

From (22)

$$dM = - \frac{1}{2} \frac{\Lambda_a}{Q_a} dM'v^2 ,$$

from which,

$$\boxed{\Gamma = \alpha_\Gamma + \alpha_N k \frac{v_r}{v} + \frac{1}{2} \alpha_{\Lambda_a} k \frac{a \cdot \Lambda_a}{Q_a} v_a v} \qquad (24)$$

Determination of $\vec{k}$

Take an element $d\sigma$ of the frontal surface area S, whose normal makes an angle $\theta$ with $\vec{v}$ (Figure 3). The mean normal component of the velocity $v_r$ of the molecules scattered (according to Knudsen's law) by a wall is equal to $(2/3) \cdot v_r$ (Ref. 4). The component along the direction of $\vec{v}$ of the momentum of the molecules reemitted by the element $d\sigma$ is:

$$\frac{2}{3} dM' \frac{d\sigma}{S} v_r \cos^2\theta$$

Integrating over the frontal surface S, we obtain:

$$k \cdot dM'v_r = \frac{2}{3} \frac{dM'}{S} v_r \iint_S \cos^2\theta d\sigma$$

$$k = \frac{2}{3S} \iint_S \cos^2\theta d\sigma \qquad (25)$$

which gives $k = 2/3$ for a plane surface of incidence and $k = 4/9$ for a spherical surface of incidence.

When the screen effect is small, it can be shown that $\alpha_\Gamma \approx \alpha_N \approx \alpha_\Lambda$. For most natural meteorites, the screen effect is negligible $\alpha_\Gamma = \alpha_N = \alpha_\Lambda = 0$. Equation (24) becomes:

$$\Gamma = 1 + k\frac{v_r}{v} + \frac{1}{2}k\frac{\Lambda_{a,o}}{Q_a}v_a v^{5/3} \tag{26}$$

Two cases must be considered.

a) Stony Meteorites

$a \approx 1$; $v_a \approx 4$ km/sec; $\Lambda_{a,o} = 4 \cdot 10^{-6}$; $Q_a = 1.8 \cdot 10^{11}$ erg$\cdot$g$^{-1}$

$v_r = 3$ km/sec for $v = 10$ km/sec, for example

$v_r = 6$ km/sec for $v = 60$ km/sec, for example

We obtain, for the three $\Gamma$'s:

$\Gamma = 1 + 0.20 + 0.03 \approx 1.2$ for $v = 10$ km/sec
$\Gamma = 1 + 0.09 + 0.18 \approx 1.3$ for $v = 30$ km/sec
$\Gamma = 1 + 0.07 + 0.60 \approx 1.7$ for $v = 60$ km/sec

The third term for $\Gamma$ is because of the impact sputtering, and predominates only at the high speeds ($v \gtrsim 40$).

b) Iron Meteorites

$v_r = v\sqrt{1 - a}$; Equation (24) becomes:

$$\Gamma = 1 + k\sqrt{1-a} + \frac{1}{2}k\frac{a\Lambda_{a,o}}{Q_a}v_a v^{5/3} \tag{27}$$

$a \approx 0.75$; $v_a \approx 4$ km/sec; $\Lambda_{a,o} = 2.5 \cdot 10^{-7}$; $Q_a = 1.8 \cdot 10^{11}$ erg$\cdot$g$^{-1}$

$\Gamma = 1 + 0.33 + 0.001 \approx 1.3$ for $v = 10$ km/sec
$\Gamma = 1 + 0.33 + 0.03 \approx 1.35$ for $v = 60$ km/sec

$\Gamma$ is practically independent of the meteorite speed $v$. The third term for $\Gamma$ is because of the impact sputtering and is always negligible.

## 6.2 Variation of the Mass by Impact Stripping

For the decrease of mass, both sides of (22) are divided by the deceleration equation (5). If the screen effect is assumed to be weak or nil, the $\alpha$ coefficients are practically the same, and are eliminated from the resulting equation. We get:

$$M = M_o \exp\left\{\frac{3}{16} \frac{a\Lambda_{a,o}}{\Gamma Q_a} \left(v^{8/3} - v_o^{8/3}\right)\right\} \tag{28}$$

with $\Gamma$ being independent of v; and with $M_o$, $v_o$ being the initial values.

Table 4 gives the values for $\frac{\Delta M}{M_o} = \frac{M_o - M}{M_o}$ as a function of $\frac{\Delta v}{v_o}$, for stony and iron meteorites, and for three values of $v_o$. In practice, the decrease of mass by impact sputtering is negligible for ion meteorites, except at the very high speeds. The decrease of mass is even more significant for stony meteorites. These values are calculated by taking $\Gamma = 1$, $Q_a = 1.8 \cdot 10^{11}$ $erg \cdot g^{-1}$; $\Lambda_{a,o} = 4 \cdot 10^{-6}$ (stony meteorites) and $\Lambda_{a,o} = 2.5 \cdot 10^{-7}$ (iron meteorites). In practice, $\Gamma$ increases with v for stony meteorites, and the residual masses are slightly greater at high speeds than those derived in Table 4.

## 6.3 Variation of the Speed by Impact Stripping

From equations:

$$(5) \qquad M \frac{dv}{dt} = - \Gamma \rho S v^2 , \quad \text{where } \rho = \rho(z),\ v = v(z)$$

$$(3) \qquad \rho(z) = \rho_h e^{-\frac{z-h}{H_h}}$$

$$dz = - v \cos\zeta \, dt \qquad \text{where } \zeta \text{ is the zenith of the meteorite radiant,} \tag{29}$$

we obtain, assuming M constant (see Table 4), $\Gamma$ constant (see the previous) and S constant:

$$v(z) = v_o \exp\left[- \frac{\Gamma \cdot H_h}{\cos\zeta} \cdot \frac{S}{M} \cdot \rho(z)\right] \tag{30}$$

For $\Delta v = v_o - v$, not too large (which supports the fact that M is constant):

$$\frac{\Delta v}{v_o} = \frac{\Gamma H_h}{\cos\zeta} \frac{S}{M} \rho \tag{31}$$

On the other hand, from (1):

$$\frac{S}{M} = \frac{A}{\delta^{2/3}} M^{-1/3}$$

with A = the shape factor of the meteorite, and with $\delta$ = the density of the meteorite.

For similar bodies, $S/M \simeq M^{-1/3}$, hence, $\Delta v/v_o$ (not too large) is inversely proportional to the size of the meteorite. The values of $\Delta v/v_o$ were calculated for $\Gamma = 1$, $\delta = 3\ g/cm^3$ (stony meteorites) $\zeta = 0^o$, $\rho(z)$ according to ARDC, 1959, for several values of R, and are listed in Table 5.

In summation, the decrease in speed, resulting from impact sputtering, is very small for all meteorites, except for particles of the order of $10\mu$ or less. The decrease of mass, resulting from impact sputtering, is also generally very small.

## 7. Heating of the Meteorites Before Vaporization

To treat this problem we consider: (1) meteorites of very large dimensions (at least of the order of a few millimeters), which heat up only superficially (see Section 7.1); and (2) meteorites of smaller dimensions, whose total mass heats up almost uniformly. This second case is that of most natural meteorites (see Section 7.2).

### 7.1 Meteorites with Nonuniform Heating

During the heating up process of meteorites, temperature is not uniform, and a heat flux is therefore established; this heat flux goes from the (instantaneous) frontal surface to the back surface. We shall later show (Section 7.1.3) that the minimum dimensions of such meteorites are about 1 mm for stony bodies, and a few millimeters for iron bodies.

We neglect, with respect to the energy received by the meteorite, the thermal radiation of the meteorite and the energy spent by the impact sputtering. We assume that the screen of reemitted air molecules is transparent enough for us to take $\alpha \simeq 1$, from which $\Lambda \simeq a$. From Tables 2 and 3 we must satisfy the following:

$$R \lesssim 5 \text{ mm (stony meteorites), and}$$
$$R \lesssim 5 \text{ cm (iron meteorites).}$$

We have seen that, for these bodies, we can take $v = v_o$ = constant, up to the start of vaporization. By applying:

$$(3) \qquad \rho(z) = \rho_h \cdot e^{-\frac{z-h}{H_h}} \qquad h \leq z$$

and

$$(29) \qquad z = z_o - v_o \cos\zeta \cdot t$$

we obtain the flux of energy received per unit surface area of the meteorite ($z_o$ is an arbitrary altitude corresponding to $t = 0$):

$$W(t) = \frac{1}{2} \Lambda \rho v^3 = \frac{1}{2} a \, \rho(z_o) \, v_o^3 \exp \frac{v_o \cos\zeta}{H} t \qquad (32)$$

1. We consider the simplified case of a cylindrical meteorite, whose permanent surface of incidence is a right angle cross section (Ref. 14). We assume that the back surface is at the temperature of the surroundings. This leads us to the problem of the propagation of heat in an infinite bar. Let:

$\theta(x,t)$ be the rise in temperature from the initial value (ambient temperature), at the point of abscissa $x$ (frontal surface at $x = 0$), and at time $t$.
$k$ be the coefficient of thermal conductivity of the material, and
$\chi$ be the coefficient of thermometric conductivity.

$$\chi = k/\delta C_p \qquad (33)$$

where $\delta$ is the density of the material and $C_p$ is its specific heat. The thermal conduction equation is:

$$\frac{\partial \theta}{\partial t} - \chi \frac{\partial^2 \theta}{\partial x^2} = 0 \qquad (34)$$

with the conditions,

$$\theta(x, -\infty) = 0$$
$$\left(\frac{\partial \theta}{\partial x}\right)_{x=0} = -\frac{W(t)}{k}$$

The solution is well known. We obtain:

$$\theta(x,t) = \frac{x_o}{\kappa} W(t)\, e^{-\frac{x}{x_o}}$$

$$= \theta(0,t)\, e^{-x/x_o}$$

with

$$x_o = \sqrt{\chi} \sqrt{\frac{H_h}{v_o \cos\zeta}} \tag{35}$$

The rise in temperature of the surface of incidence is:

$$\theta(0,t) = \frac{x_o}{\kappa} W(t)$$

from which,

$$\theta(0,z) = \frac{x_o}{\kappa} W(z)$$

$$\theta(0,z) = \frac{1}{2}\, a\, \frac{\sqrt{\chi}}{k} \sqrt{\frac{H_h}{\cos\zeta}}\, v_o^{5/2} \rho(z_o) \exp \frac{z_o - z}{H_h}$$

$$\theta(0,z) = \frac{1}{2}\, a\, \frac{\sqrt{\chi}}{k} \sqrt{\frac{H_h}{\cos\zeta}}\, v_o^{5/2}\, \rho(z) = \frac{x_o}{\kappa} W(z) \tag{36}$$

Numerical values of $\chi$, (Ref. 1):

a) Compact stony meteorites:

$k \simeq 3 \cdot 10^5$ erg (cm·sec·degree)$^{-1}$

$C_p \simeq 10^7$ erg (g·degree)$^{-1}$

$\delta \simeq 3.5$ g/cm$^3$

from which,

$$\chi \simeq 0.9 \cdot 10^{-2} \cdot cm^2 s^{-1}$$

b) Porous stony meteorites:

$k \simeq 2 \cdot 10^4$ erg (cm·sec·degree)$^{-1}$

$C_p \simeq 10^7$ erg (g·degree)$^{-1}$

$\delta \simeq 1$ g/cm$^3$

from which,

$$\chi \simeq 2 \cdot 10^{-3} \cdot cm^2 s^{-1}$$

c) Iron meteorites:

$k \simeq 3 \cdot 10^6$ erg (cm·sec·degree)$^{-1}$ (at 800 C)

$C_p \simeq 7 \cdot 10^6$ erg (g·degree)$^{-1}$

$\delta \doteq 7.6$ g/cm$^3$

from which,

$$\chi \simeq 6 \cdot 10^{-2} \text{ cm}^2 \text{s}^{-1}.$$

Table 6 shows the values for $x_o$, deduced from the previous numerical values obtained from (35) (for $\zeta = 0^o$ and H = 7 km), for three values of $v_o$:

$x_o < 0.5$ mm for stony meteorites,

$x_o \lesssim 1.5$ mm for iron meteorites.

2. We consider the case of a meteorite in rapid rotation, with dimensions $\gg x_o$. We can assume that the center remains at the initial temperature. Assuming that the thermal radial flux is uniform over all of the surface, and referring to the preceding case of the semi-infinite bar, we obtain:

$$\theta_{rot}(0,z) = \frac{1}{4}\,\theta(0,z) \qquad \text{with } \theta(0,z) \text{ given by (36).}$$

3. We consider the case of a meteorite of dimensions comparable with $x_o$. The method of images (Ref. 7) permits us to proceed from the solution of the problem of the semi-infinite bar to that of a finite bar. Let $\ell$ be the length of the bar. We find, (Ref. 1):

$$\theta_1(x,z) = \theta(0,z)\left(1 + \frac{e^{\frac{2x}{x_o}} + 1}{e^{\frac{2\ell}{x_o}} - 1}\right) e^{-\frac{x}{x_o}} \tag{37}$$

with $\theta(0,z)$ given by (36).

For example, for: $\ell = x_o$ , $\theta_1(\ell,z) \simeq \frac{1}{2}\theta_1(0,z)$

$\ell = 2x_o$ , $\theta_1(\ell,z) \simeq \frac{2}{7}\theta_1(0,z)$

Thus we can assume for $\ell > 2x_o$ that the back face does not heat up. $x_o$ is given by (35), and this condition is written:

$$\ell > 1 \text{ mm (for stony meteorites)},$$
$$\ell > 3 \text{ mm (for iron meteorites)}.$$

The temperature of the impact surface of a meteorite is:

$$T = T_o + \theta,$$

where $T_o$ is the initial temperature of the meteorite, $\theta$ being given by (36) or (37), depending on the case considered. The temperature of the surface of impact of a nonrotating meteorite ($0.5 < R \lesssim 5$ mm for a stony body and $1.5 < R \lesssim 50$ mm for an iron body), obtained from (36), is shown in Figure 4 as a function of z, for $\zeta = 0°$, and for $v_o = 15$, 30 and 60 km/sec. For $\zeta \neq 0$,

$$T(z) = T_o(z) + \frac{\theta(z)}{\sqrt{\cos\zeta}}$$

The altitudes z(T), corresponding to the same temperature, for a meteorite having a permanently plane collision surface, and for a spherical meteorite under rapid rotation, are about 10 km apart. The corresponding altitude for a meteorite of analogous dimensions, but of any shape is between the previous two extreme values.

Validity of Equation (36). This equation is valid up to the vaporization temperatures of compact stony meteorites, with $T_v = 2300°$ to $2500°$, and of iron meteorites, with $T_v = 2400°$ to $2800°$. Equation (36) is valid for porous stony meteorites, up to $T = 1900°$ to $2000°$; above these temperatures, thermal radiation becomes important.

## 7.2 Meteorites Having a Uniform Temperature

We can consider that the temperature of a meteorite remains uniform if its dimensions are less than $x_o$ (Section 7.1). In other words:

$R < 0.5$ mm for a compact stony meteorite, and
$R < 1.5$ mm for an iron meteorite.

We shall also assume that for compact stony meteorites:

$$R > 10\ \mu$$

so that we will be able to neglect the deceleration of the meteorite before its vaporization (Section 6.3). All these conditions are satisfied for most natural radio meteors.

The energy received by the meteorite up to instant t is:

$$E(t) = S\int_{\infty}^{t} W(t)dt = -\frac{S}{v_o \cos\zeta}\int_{\infty}^{z} W(z)dz$$

Taking into account (3) and (32), the expression for E(t) becomes:

$$E(t) = \frac{1}{2}\frac{a\ H_h}{\cos\zeta} S v_o^2 \rho(z) \qquad (39)$$

Generally, the energy E(t) received is transformed partly into heat and partly into energy dissipated by thermal radiation. We can therefore write:

$$\frac{dE(t)}{dt} = MC_p \frac{dT}{dt} + \beta\sigma(T^4 - T_o^4)\ S' \qquad (40)$$

where T is the temperature of the meteorite, $T_o$ is its initial temperature (temperature of thermal equilibrium with the surrounding medium), $\beta$ is the emissivity factor, $\sigma = 5.71 \cdot 10^{-5}$ erg·cm$^{-2}$sec$^{-1}$ degree$^{-4}$, and S' is the total surface area of the meteorite.

a) It can be shown (Refs. 1 and 2) that for particles of dimensions less than 10 $\mu$ (micrometeorites), the radiated energy predominates. We shall return to this case in more detail (Section 7.3).

b) For particles of dimensions greater than 10$\mu$ (radio meteors), the energy transformed into heat predominates over the radiated energy. The temperature increase $\theta(t)$ is therefore given by:

$$\theta(t) = \frac{E(t)}{M \cdot C_p}$$

or, from (39):

$$\boxed{\theta(t) = \frac{1}{2} \frac{aH_h}{\cos\zeta} \frac{S}{MC_p} v_o^2 \rho(z)} \tag{41}$$

where $C_p = 10^7$ erg (g·degree)$^{-1}$ for stony meteorites, and $C_p = 7 \cdot 10^6$ erg (g·degree)$^{-1}$ for iron meteorites.

7.3 Micrometeorites (Refs. 1 and 15)

By definition, these are meteorites of dimensions less than $10\mu$. From what was observed previously (Section 6), it is no longer possible to neglect the decrease in speed resulting from impact sputtering. The heating is given by (40), which becomes (with $\beta = 1$):

$$T^4 = T_o^4 + \frac{SW(t)}{\sigma S'}$$

$$T^4 = T_o^4 + \frac{1}{2} \frac{a}{\sigma} \frac{S}{S'} \rho v^3 \tag{42}$$

Equation (42) shows that the rise in temperature is proportional to $W^{1/4}(t)$, and is no longer proportional to $W(t)$, as for meteorites of greater dimensions (Equation 36).

The condition under which we can neglect the first term of expression (40) for $dE(t)$ is written, taking (39) into account:

$$MC_p T(t) << S \int_{-\infty}^{t} W(t)dt \leq \frac{1}{2} \frac{aH_h}{\cos\zeta} Sv_o^2 \rho \tag{43}$$

By applying (42) and assuming $T^4 >> T_o^4$, this condition becomes:

$$\sigma \frac{H_h}{C_p \cos\zeta} \frac{S'T^3}{M\, v_o} >> 1 \tag{44}$$

Example. Spherical meteorite: (45) $\frac{S'}{M} = 4\frac{S}{M} = \frac{3}{R\delta}$, from which:

$$R << 3 \frac{\sigma}{C_p\delta} \frac{H_h}{\cos\zeta} \frac{T^3}{v_o} \tag{46}$$

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If, in addition, the meteorite is a stony one:

$\delta = 3.5\ g/cm^3$ $\quad C_p = 10^7$ erg $(g \cdot degree)^{-1}$

$T = T_f \simeq 1700^\circ$ K $\quad v_o = 30$ km/sec

$H_h = 7$ km $\quad \zeta = 0^\circ$

(46) becomes: $R \ll 60\mu$.

During the entry of the meteorite into the atmosphere, the increase of temperature, which is related to the increase of $\rho$, is followed by a decrease, because of the decrease of v. For sufficiently small particles, the maximum temperature reached is less than $T_f$. From equations (30) and (42), we obtain:

$$T^4 = T_o^4 + \frac{1}{2}\frac{a}{\sigma}\frac{S}{S'}\, v_o^3\, \rho \exp\left(-3\frac{\Gamma H_h}{\cos\zeta}\frac{S}{M}\rho\right) \text{ où } \rho = \rho(z) \qquad (47)$$

The values of T can be calculated by means of (47), assuming that the decrease in mass resulting from impact stripping is negligible, and that $\Gamma$ is constant (which is a valid assumption except for very rapid stony bodies, where $v > 50$ km/sec). These values are shown in Figure 5 for spherical stony micrometeorites ($\delta = 3\ g/cm^3$; $\Gamma = 1$; $a = 1$; $\zeta = 0^\circ$).

The altitude corresponding to the maximum temperature (given by $\rho$): $dT/d\rho = 0$

$$(T_{max}) = \frac{1}{3}\frac{\cos\zeta}{\Gamma H_h}\frac{M}{S} \qquad (48)$$

$$v(T_{max}) = v_o\, e^{-1/3} = 0{,}72\ v_o \qquad (49)$$

$$T^4_{max} = \frac{1}{6e}\frac{a}{\sigma}\frac{\cos\zeta}{\Gamma\ H_h}\frac{M}{S'}v_o^3 \qquad (T_o^4 \ll T^4) \qquad (50)$$

The inequality $T_{max} \leq T_f$ defines a maximum for R, by using (48):

$$R \leq 18\ e\ \frac{c}{a}\frac{\Gamma\ H_h}{\cos\zeta}\frac{T_f^4}{v_o^3\delta} = R_{max} \qquad (T_f\text{: fusion temperature}) \qquad (51)$$

The particles with $R < R_{max}(T_f)$ are the micrometeorites of Whipple (Ref. 15). The values for $R_{max}$ and $\rho(R_{max})$ are indicated in Table 7 (for stony particles, $\delta = 3$ g/cm$^3$, $a = 1$, $\Gamma = 1$, $T_f = 1600^\circ$ K, and for $\zeta = 0^\circ$).

Figures 6, 7 and 8 show the essential results for the study of: (1) the transparency of the screen due to the reemitted particles, (2) the deceleration of the meteorite before vaporization, and (3) the heating up of the meteorite before vaporization.

## 8. Vaporization of the Meteorite

We have seen (Section 7) that meteorites of dimensions greater than 10$\mu$ keep heating up while they descend through the atmosphere. Starting from a certain altitude, they reach their temperature of vaporization.

### 8.1 Calculation of the Parameters which Characterize the Vaporization

The vaporization of a solid or liquid is characterized by two quantities: $N_v$, the number of vaporized molecules per second per square centimeter of area; and p, the pressure of saturated vapor. It can be shown (Ref. 1) that p is given by:

$$p = \sqrt{\frac{2\pi \cdot kT}{m'}} \cdot \frac{N_v \cdot m'}{b}$$

where m' is the mean molecular mass of the meteorite, and b is the sticking coefficient (fraction of the condensing vapor molecules incident on 1 cm$^2$ of the body); b = 1 for metals (Ref. 9), and B < 1 for stony meteorites.

Overall Specific Energy of Vaporization: Q

This is the energy necessary to raise the temperature of 1 gram of a solid body for its fusion and its vaporization.

$$Q = \frac{L_o}{\mathcal{M}} + \frac{3}{2} k\, T_v$$

where $L_o$ = 93,000 calories (mole)$^{-1}$ is the specific heat at 0° K, $\mathcal{M}$ the

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molar mass of the body, and $T_v$ its temperature of vaporization. We find $Q = 7.5 \cdot 10^{10}$ erg$\cdot$g$^{-1}$ for iron. We take (2): $Q = 8.08 \cdot 10^{10}$ erg$\cdot$g$^{-1}$ for stony meteorites. We shall use the following average value:

$$Q = 8 \cdot 10^{10} \text{ erg} \cdot \text{g}^{-1} ,$$

for the whole set of meteorites.

Boiling

When boiling takes place, all of the energy received is used by the vaporization. The mass $N_v m'$, vaporized per cm$^2$ per second is given by:

$$N_v m' = \frac{W}{Q} = \frac{1}{2} \frac{\Lambda}{Q} \rho v^3 \tag{54}$$

The pressure of saturated vapor is, from (53), given by:

$$p = \frac{1}{b} \sqrt{\frac{2\pi kT}{m'}} \; \frac{\Lambda}{2Q} \rho v^3 \tag{55}$$

The boiling starts when the saturated vapor pressure p is greater than or equal to the aerodynamic pressure,

$$P = \Gamma \cdot \rho \cdot v^2 \tag{56}$$

which is exerted on the meteorite. From (55) and (56), the condition $p \geq P$ becomes:

$$T \geq \frac{m'}{2\pi k} \cdot \frac{b^2}{\xi^2 v^2} \tag{57}$$

The right hand side represents the boiling temperature of the meteorite. Remember that:

$$\xi = \frac{\Lambda}{2\Gamma Q} . \tag{58}$$

We shall see (Section 9) that we can adopt the following average value, $\xi = 2 \cdot 10^{-12}$.

a) Iron Meteorites: $b = 1$. We deduce from (57) that:

$$T > 12000^\circ \text{ K if } v = 15 \text{ km/sec}$$
$$T > 3000^\circ \text{ K if } v = 30 \text{ km/sec}$$
$$T > 750^\circ \text{ K if } v = 60 \text{ km/sec}$$

Boiling is impossible at speeds approximately less than 30 km/sec.

b) Stony Meteorites: $b < 1$, but its value is poorly known. We can simply say that boiling always takes place at the very high speeds.

## 8.2 Vaporization of Millimetric or Greater Meteorites

a) Iron Meteorites

At equilibrium between the liquid and vapor phases, we have (Ref. 16):

$$\log_{10} p = 13.53 - \frac{21400}{T} \qquad \text{in c.g.s. .} \tag{59}$$

The total vaporization energy $QN_v m'$ (in $\text{erg}\cdot\text{cm}^2/\text{sec}$) is, from (53) and (59):

$$\log_{10}(QN_v m') = 20.93 - \frac{1}{2}\log_{10} T - \frac{21400}{T} \tag{60}$$

with

$$Q \simeq 8\cdot 10^{10} \text{ erg}\cdot\text{g}^{-1}.$$

In Table 8, we show, as a function of T, the values of:

$QN_v m'$ from (60);

$W(T)$ from (36), taking $\zeta = 0^\circ$, $H_0 = 7$ km

$T = \theta + T_0$ ($T_0$ initial temperature

of the meteorite), $a = 0.75$

Remarks

1. When $QN_v m'$ becomes a sizeable fraction of W, the screen resulting from the vaporized molecules is no longer negligible. Equation (36), as established for $\alpha \simeq 1$, is no longer applicable (see the following).

2. Table 8 is established for a meteorite having a permanent plane frontal surface. For rotating bodies, the same temperatures are reached for greater values of $W(z)$; therefore, for lower altitudes (by 10 km approximately).

b) Compact Stony Meteorites

In the absence of data on the vapor pressures of stony bodies, we have to take (59) and (60) as being applicable to these bodies (the mean molar masses of stony and iron meteorite vapors are almost the same).

Table 8 gives, as a function of T, the values of:

$QN_V m'$ from (60); and

$W(T)$ from (36), taking $T = \theta + T_0$; $a = 1$

$\zeta = 0^\circ$; $H_o = 7$ km

Because of their lower thermal conductivity, the stony meteorites reach the same temperatures as the iron meteorites at greater altitudes.

c) Porous Stony Meteorites

Before the start of vaporization ($1500 < T < 2000^\circ$ K), thermal radiation represents a sizeable fraction of the incident energy of the air molecules. The subsequent increase of the flux W entails an increase in vaporization whose energy becomes greater than the radiated energy.

## Variation of the Temperature as a Function of the Altitude

Figures 9 and 10 show examples of variations of the meteorite temperature T as a function of its altitude z, during the two successive phases of heating (Section 7) and intense vaporization (Section 8).

a) During the heating period. The rise in the temperature $\theta$ was calculated from (36). We have assumed $\zeta = 0$, $H_o = 7$ km, and the values for k and $\chi$ are given in Section 7, those for a are given in Section 4.3.

b) During the vaporization period. The function of T versus z is obtained by writing that the energy $QN_V m'$ necessary for the vaporization, and given by (60), is equal to the energy supplied to the meteorite.

$$QN_V m' = \frac{1}{2} \Lambda \rho v^3$$

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Altitude of Appearance of Meteors

In practice, these are the altitudes where an intense vaporization is initiated. From (36) and (3), the rise in temperature of the surface of incidence is written:

$$\theta(z) = \frac{1}{2}\, a \frac{\sqrt{\chi}}{k} \sqrt{\frac{H_h}{\cos\zeta}}\, v_o^{5/2} \rho_h\, e^{-\frac{z-h}{H_h}} \quad . \tag{61}$$

Let $z_1$ be the altitude of the start of intense vaporization. We have:

$$z_1(v_o,\zeta) = h + H_h\left\{\log\left(\frac{a}{2}\,\frac{\sqrt{\chi}}{K}\,\frac{\sqrt{H_h}\,\rho_h}{\theta(z_1)}\right) + \frac{5}{2}\log v_o - \frac{1}{2}\log\cos\zeta\right\} \tag{62}$$

From Figures 9 and 10, we have $2100 < T(z_1) < 2800^{\circ}$ K (70 to 90 km $< z_1$ $<$ 100 to 120 km). Roughly, $1800 < \theta(z_1) < 2600^{\circ}$ K. Remember that the thickness of the layer where the meteors start to be visible was estimated to be 10 km. Figure 11 and Table 9 show: the calculated altitudes of the meteor appearance layers (vertical trajectory, homotropous atmosphere $H_o$ = 7 km); and the altitudes of appearance of sporadic meteors and of the principal showers (Refs. 20, 29 and 30).

8.3 Vaporization of Submillimeter Meteorites

These meteorites have practically a uniform temperature, and completely melt before the vaporization takes place. Figure 12 shows curves $T(z)$ for iron meteorites, for $v_o$ = 15, 30 and 60 km/sec and R = 100 $\mu$, 10$\mu$ and 1$\mu$.

9. Screen Due to the Molecules Vaporized from the Meteorite

The transparency coefficient $\alpha$ is determined with the same method as for reemitted air molecules (Section 5). However, the essential difference between the two is that the transparency cannot be close to unity ($\alpha \gtrsim 0.9$) unless the meteorites have dimensions definitely less than a millimeter ($R \lesssim 100\mu$). For the rest of the meteorites, it is no longer possible to make the approximations of the weak screen, which were permitted for the reflected air molecules.

From (54), the number of molecules vaporized per square centimeter per second is:

$$N_v = \frac{W}{m'Q} = \frac{1}{2}\,\frac{\Lambda}{m'Q}\,\rho v^3 = \frac{1}{2}\,\frac{a\alpha_\Lambda}{m'Q}\,\rho v^3 \tag{63}$$

where $\alpha_\Lambda$ is the transparency coefficient of the vaporized molecules for the flux of energy and m' the mean molecular mass of the meteorite. Equation (15) becomes:

$$\alpha_\Lambda = e^{-\beta\Sigma_v} = \exp\left(-\frac{16}{3}\,\beta N_v\,d'^2\,\frac{R}{v_T}\right)$$

where d' is the mean molecular diameter of the meteorite and $v_T$ is the speed of the vaporized molecules.

$$\alpha_\Lambda = \exp\left(-\frac{8}{3}\,\beta(\Lambda)\;a\,\frac{d'^2}{m'Qv_T}\,R\rho V^3\alpha_\Lambda\right) \tag{64}$$

We have taken $\beta = \beta(\Lambda)$, since the collisions modify the space distribution of vaporized molecules while the screen becomes denser. This is an unknown function, and (64) cannot be used to determine $\alpha_\Lambda$.

Condition for the Screen Effect to be Weak.

If the screen effect is weak, (64) becomes:

$$1 - \alpha \simeq \frac{8}{3}\,\beta a\,\frac{d'^2}{m'Qv_T}\,R\rho v^3 \tag{65}$$

where $\beta$ is no longer dependent on $\Lambda$. For a stony meteorite $\beta \simeq 0.2$.

With $a = 1$; $d' = 3\cdot10^{-8}$ cm; $m' = 82\cdot10^{-24}$ g; $Q = 8\cdot10^{10}$ erg$\cdot$g$^{-1}$; and $v_T \simeq 1.5$ km/sec the condition $\alpha > 0.9$ is written:

$$R\rho v^3 < 2\cdot10^8 \tag{66}$$

On the other hand, the vaporization of spherical stony meteorites less than a tenth of a millimeter in dimensions is established at about $T = 2000^\circ$ K; in other words, from (42), when $\rho v^3 \gtrsim 10^{10}$.

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These last two inequalities are simultaneously satisfied for[1]:

$$R < 0.2 \text{ mm}.$$

We can therefore say that the screen effect is weak most of the time for the natural meteorites which are observed by radio means.

### Numerical Values for the Drag Coefficient $\Gamma$ in the Case of a Weak Screen ($\alpha > 0.9$)

We operate in the same way as for deriving equation (26). Neglecting the impulse of the molecules removed by impact, we obtain:

$$\Gamma \simeq \alpha \cdot \left(1 + k \frac{v_r}{v} + \frac{1}{2} k \frac{a}{Q} v_T \, v\right) \tag{67}$$

where $v_r$ is the speed of the reemitted molecules, and $v_T$ is the speed of vaporized molecules.

a) Stony Meteorites

With the values $v_r \simeq 1$ km/sec; $Q = 8 \cdot 10^{10}$ erg$\cdot$g$^{-1}$; $a \simeq 1$; $v_T \simeq 1$ km/sec; $k \simeq 0.5$; equation (67) becomes:

$$\Gamma \simeq \alpha \cdot \left(1 + \frac{0.5}{v} + 3 \cdot 10^{-2} \, v\right) \simeq \alpha (1 + 3 \cdot 10^{-2} \, v), \tag{68}$$

where v is expressed in kilometers per second.

---

[1] A calculation similarly performed for meteorites of greater size, using (36) instead of (42), shows that the transparency $\alpha$ is weak from the beginning of the vaporization. Table 10 gives values of $\alpha_A$ as a function of $\rho v^3$, for two values of R. In reality, the values of $\alpha_A$ tend to be greater than those indicated in Table 10. Indeed: a) The right angle cross section S generally decreases during the vaporization. b) The collisions of the air molecules against the vaporized molecules increase in number and create, on the average, an increase of the temperature of the cloud, and therefore an increase in the speeds of the particles which belong to this cloud. c) The mutual collisions between the vaporized molecules lead, on the average, to an increase in the time of flight of these molecules in front of the meteorite.

b) Iron Meteorites

With $v_r = v \cdot \sqrt{1 - a}$, and the values $a \simeq 0.75$; $k \simeq 0.5$; $Q = 8.10^{10}$ $erg \cdot g^{-1}$; $v_T \simeq 1$ km/sec, equation (67) becomes:

$$\Gamma \simeq \alpha \cdot (1.25 + 2 \cdot 10^{-2}\, v), \tag{69}$$

where v is expressed in kilometers per second.

Relations (68) and (69) assume that the transparency $\alpha$ is fairly close to 1. When the conditions of the motion were such that the screen was a dense one, the numerical values of $\Gamma$ and $\Lambda$ were obtained from photographs of meteors or of hypersonic projectiles (Refs. 17 and 18). Experimental values of $\Gamma$:

| | |
|---|---|
| Meteorites | $\Gamma_{average} = 0.5$ (Ref. 17) |
| Iron or aluminum projectiles | $\Gamma_{average} = 0.42$ for $v \lesssim 6$ km/sec (Ref. 18) |

Experimental Determination of the Parameter $\xi = \Lambda/2\Gamma Q$ see (7)

The photographic observations of meteors do not make it possible to obtain $\Gamma$ and $\Lambda$ separately. Since $\Gamma$ varies within a relatively narrow interval only, $\xi$ is determined by observation, then, knowing Q from laboratory measurements, $\Lambda$ is calculated. The luminous intensity of a meteor is taken from the relation:

$$I = - \frac{\tau}{4\pi} \frac{1}{2} \frac{dM}{dt} v^2, \tag{70}$$

where $\tau = \tau(v)$ is a luminosity factor. For simplification, the residual mass is assumed zero when the meteor disappears. Equation (70) becomes:

$$M = 8\pi \int_{t}^{t_2} \frac{I(t)}{\tau v^2}\, dt \tag{71}$$

where $t_2$ is the instant when the meteor disappears. Combining (7), (70) and (71), we obtain:

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$$\xi = \frac{I(t)}{\tau v^3 \frac{dv}{dt} \int_{t_2}^{t} \frac{I(t)}{\tau v^2} dt} \tag{72}$$

Here, v and dv/dt are determined from photographs taken at two locations, with an objective equipped with a rotating blade shutter (Ref. 8). In the first approximation, we take $\tau$ (v) = constant. Another very simple expression is $\tau (v) = \tau_o v$ (Refs. 19 and 20).

From photographs of 36 meteors, Jacchia (Ref. 19) was able to obtain 55 values for $\xi$ (there are several measurement points on the same track of certain meteors). That author finds:

$$\log \bar{\xi} = -11.75; \quad \bar{\xi} = 1.8 \cdot 10^{-12} \quad (5 \cdot 10^{-13} < \xi < 4 \cdot 10^{-12})$$

Taking $Q = 8 \cdot 10^{10}$ erg$\cdot$g$^{-1}$, $\Gamma \simeq 0.5$, the values $\Lambda = 0.32$ and $\Lambda = 0.04$ to correspond to the measured extreme values of $\xi$.

We shall sum up the various results from the photograph observations, which were compared with laboratory measurements and with calculations, taking the following average values:

(1) for meteorites of more than 10 cm (small fireballs) $\Lambda \lesssim 0.05$

(2) for meteorites of the order of 1 cm (very bright visual meteors) $\Lambda \simeq 0.15$

(3) for meteorites of the order of 1mm (ordinary visual meteors) $\Lambda \simeq 0.3$ to 0.5

(4) for smaller meteorites (most radio meteors) $\Lambda \simeq a$

Influence of $\Lambda$ on $\Gamma$

From (67):

$$\Gamma \simeq \alpha\left(1 + k\frac{v_r}{v} + \frac{1}{2} k \frac{a}{Q} v_T v\right) = \Gamma_o + \frac{1}{2} k \frac{\Lambda}{Q} v_T v =$$

$$= \Gamma_o \left(1 + \frac{1}{2} k \frac{\Lambda}{\Gamma_o Q} v_T v\right)$$

Consider a stony meteorite:

$Q = 8 \cdot 10^{10}$ erg$\cdot$g$^{-1}$; $v_T \simeq 1$ km/sec; $k \simeq 1/2$; $\Gamma_o \simeq 0.4$ from which, expressing, v in km/sec:

$$\Gamma \simeq 0.4\ (1 + 8 \cdot 10^{-2}\ \Lambda v) \tag{73}$$

$\Gamma$ increases with v, but the decrease of $\alpha$, and therefore of $\Lambda$, with the speed (16), (64) limits the $\Gamma$ variation. This can explain the choice of the value $\Gamma = 0.5$ which is used in a great number of meteor problems.

## 10. Motion of a Meteorite During Vaporization

### 10.1 Relation Between the Mass and the Speed ($\Lambda$, $\Gamma$ constant)

From (5) and (6) we have (Figure 13):

$$M(v) = M_1 \exp(- \frac{\xi}{2} (v_1^2 - v_2^2)), \tag{74}$$

where $M_1$ and $v_1$ are the values at the start of vaporization. We have

seen in Section 6 that the decreases of mass and the speed resulting from impact sputtering are very small, except for rapid particles of dimensions less than $10\mu$ approximately. We therefore have for most visible meteors (observed with a radio):

$$M_o = M_1;\ v_o = v_1$$

Equation (74) becomes:

$$M(0) = M_o\ e^{-\frac{\xi}{2} v_o^2} \tag{75}$$

v = 0 means cancellation of the initial speed, neglecting gravity.

In reality the decrease of mass, which is because of vaporization, stops before v becomes zero. The residual mass $M_{res}$ is greater than M(0). We have

$$M_{res} = M(0)\ e^{\frac{\xi}{2} v^{*2}} \qquad \text{(See Figure 13)}$$

For example: for $v \simeq 5$ to 6 km/sec and $\xi = 2 \cdot 10^{-12}$ we have $M_{res} \simeq 1.30$ M(0)*.

---

*Because of the uncertainty involved in the numerical data, we can estimate that the difference between M(0) and $M_{res}$ is small, and can be rewritten $M_{res} \simeq M(0)$.

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Table 11 gives the values of $\frac{M(0)}{M_o}$ as a function of $v_o$ for two values of $\xi$. Note that for big meteorites ($R > 10$ cm), $\xi$ is smaller (75) and is of the order of $10^{-13}$. The residual mass is therefore much greater (for $v_o = 30$ km/sec, $M(0) \simeq 0.6\ M_o$). Figure 13 also shows that the vaporization of most of the initial mass takes place while the speed has only decreased from $v_1 \simeq v_o$ by a few kilometers per second, especially when $v_o$ is large (calculations carried out with $\xi = 2.10^{-12}$).

10.2 Relation Between the Mass and the Speed ($\Lambda$, $\Gamma$ variable, screen of small density

From Section 8, the condition of a screen of small density is fulfilled only for sufficiently small meteorites ($R \lesssim 100\mu$).

From (5), (6) and (67), we obtain, after calculations, the equation:

$$\frac{dM}{M} = \frac{avdv}{2Q(1+k\sqrt{1-a}) + kav_T v} \tag{76}$$

which yields,

$$M = M_o e^{-\frac{v_o - v}{kv_T}} \left(\frac{2Q(1+k\sqrt{1-a})+akv_T v_o}{2Q(1+k\sqrt{1-a})+akv_T v}\right)^{\frac{2Q(1+k\sqrt{1-a})}{ak^2 v_T^2}} \tag{77}$$

Since the decrease of v is relatively small during the greatest part of the vaporization, we can take:

$$M = M_o \exp\left(-\frac{(v_o - v)\ v}{2Q(1+k\sqrt{1-a})+akv_T v}\right) \qquad v_o - v << 1 \tag{78}$$

Figure 14 shows also that a sizeable decrease of the mass takes place for a small decrease of v, from $v_o \simeq v_1$ (curves plotted for stony meteorites, $a = 1$; $Q = 8 \cdot 10^{10}$ erg$\cdot$g$^{-1}$, $k = 1/2$, and $v_T = 1.2$ km/sec).

10.3 Relation Between the Mass and Altitude: A) $\Lambda$ = constant approximation

The hypothesis $\Lambda$ = constant, applies also to meteorites having small dimensions and a negligible screen effect, which leads to (Section 4.4):

$$\Lambda \simeq a$$

where a remains close to 1. From Table 3, the approximation applies to most meteorites observed by radio means.

In addition, we must propose another hypothesis on the relation which relates the decrease of mass M with that of the right angle cross section S. In the simplest case where the meteorite remains similar to itself, we have:

$$\frac{S}{S_o} = \left(\frac{M}{M_o}\right)^{2/3}.$$

We shall assume that we generally have a relation of the form:

$$\frac{S}{S_o} = \left(\frac{M}{M_o}\right)^{\mu}, \tag{79}$$

where the exponent $\mu$ remains constant for a given meteorite during its motion.

Taking (79) into account, equation (6), which gives the decrease of the mass M with the time, can be written:

$$\frac{dM}{dt} = -\xi\Gamma\frac{S_o}{M_o^{\mu}} M^{\mu}\rho v^3 \tag{80}$$

where the $\Lambda$ = constant hypothesis entails $\xi$ = constant. However, M and v are related through relation (74), derived before:

$$(74) \qquad M = M_o \exp -\left[\frac{\xi}{2}(v_o^2 - v^2)\right]$$

Eliminating M from (74) and (80), and applying (3) and (29), we obtain the function of v versus the altitude z:

$$\frac{\exp\left(-\frac{\xi}{2}(1-\mu)(v_o^2-v^2)\right)}{v}dv = \frac{\Gamma So}{M_o\cos\zeta}\rho(h)\, e^{-\frac{z-h}{H_h}}dz \tag{81}$$

Integrating this equation with $v_1 \simeq v_o$ we have:

$$\begin{aligned}\frac{1}{2}e^{-\frac{\xi(1-\mu)}{2}v_o^2}\left\{Ei\left(\frac{\xi(1-\mu)}{2}v_o^2\right) - Ei\left(\frac{\xi(1-\mu)}{2}v^2\right)\right\} &= \\ = \frac{\Gamma S_o H_h}{M_o\cos\zeta}(\rho(z) - \rho(z_1))\end{aligned} \tag{82}$$

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where Ei(x) is the exponential integral function: $\mathrm{Ei}(x) = \int_{\infty}^{x} \frac{e^u}{u}\, du$

Relation (82) gives v, and M can be deduced from it by using (74).

A much simpler approximate expression for M can be obtained by remarking that the greatest part of the mass is vaporized while the speed has only decreased a few kilometers per second with respect to its initial value $v_1 \simeq v_o$. Taking $v \simeq v_1 \simeq v_o$, integrating (80) yields:

$$\left(\frac{M}{M_o}\right)^{1-\mu} = 1 - (1-\mu)\frac{\xi \Gamma v_o^2}{\cos\zeta}\frac{S_o}{M_o} H_h \left(\rho(z) - \rho(z_1)\right) \tag{83}$$

In the case of a meteorite which remains similar to itself, $\mu = 2/3$, and (83) becomes linear with respect to R and $\rho$:

$$R = R_o - \xi v_o^2 \frac{\Gamma H_h}{4\delta\cos\zeta}\left(\rho(z) - \rho(z_1)\right) \tag{84}$$

Altitude $z_2$ Corresponding to the End of Meteor Visibility

If we assume a constant speed during the whole evaporation (see the previous), we find from (83), and by taking M = 0:

$$\rho(z_2) - \rho(z_1) = \frac{M_o\cos\zeta}{(1-\mu)\xi v_o^2 \Gamma S_o H_h} \tag{85}$$

For example: spherical meteorite (constant A):

$$\rho(z_2) - \rho(z_1) = \frac{4\delta R_o\cos\zeta}{\xi v_o^2 \Gamma H_h}$$

We also deduce from (80) the altitude $z_M$ corresponding to a maximum speed of vaporization $\frac{dM}{dt}$. We obtain (still using the hypothesis $v = v_1 \simeq v_o$):

$$\rho(z_M) = (1-\mu)\,\rho(z_1) + \frac{M_o\cos\zeta}{\xi v_o^2 \Gamma S_o H_h} \tag{86}$$

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Then, from (83) and (86):

$$M_M^{1-\mu} = \mu M_o^{1-\mu} + \mu(1-\mu)\,\frac{\xi \Gamma v_o^2}{\cos\zeta}\,\frac{S_o}{M_o^{\mu}}\cdot H_h\,\rho(z_1) \quad \text{where } M_M = M(z_M) \qquad (87)$$

For ordinary visual meteors, or for very bright ones which have a sufficiently long train, we can take $(z_1)_{\rho} \ll \rho(z_M)$. We have:

$$\rho(z_M) \approx \frac{M_o \cos\zeta}{\xi v_o^2 \Gamma S_o H_h} \qquad (88)$$

$$M_M \approx \mu^{\frac{1}{1-\mu}} M_o \qquad \text{where from (80)} \qquad (89)$$

$$\left(\frac{dM}{dt}\right)_{max} = -\mu^{\frac{\mu}{1-\mu}}\,\frac{M_o v_o \cos\zeta}{H_h} \qquad (90)$$

Finally, (85) and (86) show that in most cases $z_2$ and $z_M$ are related by:

$$\rho(z_M) = (1-\mu)\ \rho(z_2),$$

which, from (3), gives:

$$z_M - z_2 = H_h \log_e \frac{1}{1-\mu}\ . \qquad (91)$$

In particular for $\mu = 2/3$:

$$z_M - z_2 = 1.1\ H_h.$$

### 10.4 Relation Between the Mass and Altitude: B) $\Lambda$ variable

For meteorites of sufficiently high mass, the screen effect cannot be neglected and $\Lambda$ must be considered variable. Using the method of the least squares to a series of experimental results obtained by Jacchia (Ref. 19), we obtain the empirical relation:

$$\xi = \frac{\xi^*}{M^{\alpha}\rho^{\beta}v^{\tau}} \qquad (92)$$

with $\xi^* = 8\cdot 10^{-8}$, $\alpha = 0.10$, $\beta = 0.27$, $\tau = 1.32$ ($M$, $\rho$ and $v$ in c.g.s.).

On the other hand, if the screen effect is sufficiently large, $\Gamma$ can be considered constant. With the hypothesis of (79) and (92), the ablation equation (80) becomes:

$$\frac{dM}{dt} = - \xi^* \Gamma \frac{S_o}{M_o^\mu} M^{\mu-\alpha} \rho^{1-\beta} v^{3-\gamma} \tag{93}$$

Taking the same simplifying assumption $v = v_1 \simeq v_o$, as in Section 10.3, we have:

$$\left(\frac{M}{M_o}\right)^{1-\mu+\alpha} = 1-(1-\mu+\alpha)\frac{\xi^*}{1-\beta} \Gamma v_o^{2-\gamma} \frac{S_o}{\cos\zeta M_o^{1+\alpha}} H_h\left(\rho^{1-\beta}(z) - \rho^{1-\beta}(z_1)\right) \tag{94}$$

Altitude Corresponding to the End of Visibility: $z_2$

Taking $M = 0$ in (94), we have:

$$\rho^{1-\beta}(z_2) = \rho^{1-\beta}(z_1) + \frac{(1-\beta)\cos\zeta\, M_o^{1+\alpha}}{(1+\alpha-\mu)\xi^* \Gamma v_o^{2-\gamma} S_o H_h} \tag{95}$$

This relation has a form close to that of (85). In the same way, we obtain relations analogous to (86), (87), (88), (89), (90) and (91):

$$\rho^{1-\beta}(z_M) = (1+\alpha-\mu)\rho^{1-\beta}(z_1) + \frac{(1-\beta)\cos\zeta M_o^{1+\alpha}}{\xi^* \Gamma v_o^{2-\gamma} S_o H_h} \tag{96}$$

$$M_M^{1+\alpha-\mu} = (\mu-\alpha)M_o^{1+\alpha-\mu} + (\mu-\alpha)(1+\alpha-\mu)\frac{\xi^* \Gamma v_o^{2-\gamma} S_o H_h}{(1-\beta)\cos\zeta M_o^\mu} \rho^{1-\beta}(z_1) \tag{97}$$

$$\rho^{1-\beta}(z_M) \simeq \frac{1-\beta}{\xi^*} \frac{\cos\zeta M_o^{1+\alpha}}{\Gamma v_o^{2-\gamma} S_o H_h} \tag{98}$$

$$M_M \simeq (\mu-\alpha)^{\frac{1}{1+\alpha-\mu}} M_o \tag{99}$$

$$\left(\frac{dM}{dt}\right)_{max} \simeq - (1-\beta)(\mu-\alpha)^{\frac{\mu-\alpha}{1+\alpha-\mu}} \frac{M_o v_o \cos\zeta}{H_h} \tag{100}$$

$$z_M - z_2 = H_h \operatorname{Log}\frac{1}{1+\alpha-\mu} = 0{,}71\ H_h \tag{101}$$

## 10.5 Deceleration of the Meteorite (constant $\Gamma$, $\Lambda$)

For the case where $\xi$ is assumed to be constant, we have already obtained a relation giving v as a function of the altitude z:

$$\frac{1}{2} e^{-\frac{\xi(1-\mu)}{2} v_o^2} \left\{ Ei\, \frac{\xi(1-\mu)v_o^2}{2} - Ei\, \frac{\xi(1-\mu)v^2}{2} \right\} = \frac{\Gamma S_o H_h}{M_o \cos\zeta} \left(\rho(z) - \rho(z_1)\right)$$

where,

$$E\,i(x) = \int_{-\infty}^{x} \frac{e^u}{u}\, du$$

is the "exponential integral" function.

Figure 15 gives the values of v as a function of z for a stony meteorite remaining spherical ($\mu = 2/3$), and having a vertical trajectory ($\zeta = 0$), with $R_o = 1$ mm, $\delta = 3$ g cm$^{-3}$, $\xi = 2 \cdot 10^{-12}$ for 3 values of $v_o$.

This example proves that the deceleration can be neglected most of the time in the most luminous part of the train.

## 11. Meteor Luminosity (Refs. 1, 2 and 8)

The spectrum of sufficiently bright meteorites is essentially a spectrum of rays due to neutral or ionized atoms of the meteorite; these atoms being excited by collisions with the air molecules. The atoms and ions identified in these spectra are, by decreasing order of frequencies:

Fe, Mg, $Mg^+$, Ca, $Ca^+$, Na, Si, $Si^+$, Ni, Mn, Cr, Al, $Fe^+$, H, N, O. A band spectrum corresponding to atmospheric nitrogen $N_2$ was also observed (Refs. 10, 21 and 22).

Since the thermal speeds $v_T$, relative to the meteorites, of the vaporized molecules are of the order of 1 to 2 km/sec ($T \simeq 2500^\circ$ K), they are small compared with the speed of the body itself. These molecules form practically a monoenergetic beam through the atmosphere, because their kinetic energies E are between approximately 15 and 1000 ev:

| | |
|---|---|
| stony meteorite | $16 \leq E \leq 560$ ev for $10 \leq v \leq 60$ km/sec |
| iron meteorite | $30 \leq E \leq 1050$ ev for $10 \leq v \leq 60$ km/sec |

The multiple collisions undergone by a vaporized molecule easily provoke the dissociation, and then the excitation (or ionization) of the neutral atoms and ions thus formed. See Table 12 for the dissociation and ionization energies of various elements (Ref. 2). See also Brun in Reference 24.

Luminosity Equation

It is believed that the average radiated power of the meteorite in the visible frequency band, between 4000 A and 7000 A, is proportional to the decrease per unit time of the kinetic energy of the vaporized molecules:

$$I = -\frac{1}{2}\tau\frac{dM}{dt}v^2 \qquad (102)$$

where $\tau$ is the luminosity coefficient for the 4000 A to 7000 A band, and $\frac{dM}{dt}$ is given by the equation for the mass decrease (80). Replacing this valve, we have:

$$I = \frac{1}{2}\tau\xi\Gamma\frac{S_o}{M_o^{\mu}}M^{\mu}\rho v^5 = \frac{1}{2}\tau\xi\Gamma\frac{A_o M_o^{\frac{2}{3}-\mu}}{\delta^{2/3}}M^{\mu}\rho v^5 \qquad (103)$$

where $\xi = \Lambda/2\Gamma Q$; is the meteorite density and $A_o$ is the initial shape factor.

The values of $\tau$, which were proposed by the observers, show a great amount of dispersion: $10^{-4} < \tau < 10^{-2}$. Öpik splits the $\tau$ coefficient into three terms whose values he calculates, for different conditions, by using experimental results of quantum mechanics: see Reference 2, Öpik in Reference 10. These three terms come from: (1) radiation of atoms which are excited by collisions with the air molecules, (2) radiation due to the thermal collision of the vaporized atoms between themselves, and (3) thermal radiation of the meteorite.

For ordinary visible meteorites, only the first term is important. Table 13 shows the fraction of dissociated molecules, and the first term of $\tau$, relative to the radiation due to collision excitation; both are a function of the speed, and are for two very different values of the dilution coefficient (ratio of the meteorite density in the vapor phase to the density of air) (2).

The calculations are performed by taking into account the following points:

(1) A collision of the second kind brings an atom from a certain level of excitation to the ground level.

(2) The vaporized atoms of the meteorite, which are several times ionized, exchange $e^-$ charges with the air molecules. From this there result simply ionized atoms which can be excited by an energy excess of the transformation. The weak radiation, due to these effects, is neglected.

(3) All the atoms coming from the molecular dissociation which is triggered by the very first collision are assumed to have an initial excitation. This assumption is largely justified for the medium and high-speed meteorites.

(4) The transition from the excitation energy of an atom to luminous energy involves the spectral sensitivity of the eye, whose curve is given.

Approximate Expression for $\tau$

By applying the results of Öpik, Whipple takes (Ref. 25):

$$\tau = \tau_o v \qquad \text{where } \tau_o = 8.5 \cdot 10^{-10} \text{sec.} \tag{104}$$

This relation is only applicable to the most brilliant meteors.

Maximum Luminous Intensity of a Meteor

If we neglect the deceleration of the meteorite, at least for a great part of the vaporization, the altitude corresponding to the maximum luminosity is, from (102) and (104), the same as the altitude corresponding to the maximum of the speed of vaporization. From (88) and (89), (103) becomes:

$$I_{max} = \frac{1}{2}\tau_o v_o^{3+p} \mu^{\frac{\mu}{1-\mu}} \frac{M_o \cos\zeta}{H_h} \; ; \quad \text{presuming} \quad \tau(v) = \tau_o v^p \tag{105}$$

Magnitude

a) Apparent visual magnitude of a star: $\mathcal{M}_{av}$

The apparent visual (av) magnitudes are defined by:

$$m_2 - m_1 = 2.5 \log_{10} \frac{L_1}{L_2} \; ; \; L_1, L_2 \text{ are luminosities.} \qquad (106)$$

The values of $m_{av}$ are found when the zenithal angle of the star is less than $45^o$ (the atmospheric absorption correction is $\geq 0.1^m$ for $\zeta \geq 45^o$). $m_{av} = 0$ corresponds approximately to the luminosity of the star Vega ($\alpha$Lyra (for $\alpha$Centauri and $\alpha$Lyra, $m_{av} = 0.1$).

b) Absolute visual magnitude of a star: $m_v$

$m_v$ is deduced from $m_{av}$ by taking the distance into account.

Example: $\alpha$Centauri A (4.3 a-l) $m_{av} = 0.1$ $m_v = 4.7$

$\alpha$Lyra ( 27 a-l) $m_{av} = 0.1$ $m_v = 0.5$

c) Absolute visual magnitude of a meteor.

This is the magnitude of a meteor which would be located at $\zeta = 0^o$, $z = 100$ km. To move from the apparent magnitude to the absolute magnitude, two corrections must be made (Figure 16):

(1) Distance effect.
(2) Atmospheric absorption, which is independent of the meteor altitude (absorption due to the troposphere), and depends on the zenithal angle of the meteor.

Öpik's relation (Ref. 26) is:

$$m_v = 6.8 - 2.5 \log_{10} I, \qquad (107)$$

where $m_v$ is the absolute visual magnitude of the meteor, and I is the radiated luminous power in the 4000-A to 7000-A band (in watts).

d) Photographic magnitude: $m_p$

The photographic magnitude of a meteor is obtained by directly comparing the meteor with the images of stars which are on the same photograph as the meteor. Generally we have: $m_p \neq m_v$.

Color index: $i = m_p - m_v$.

From relatively recent measurements (Ref. 27), i is close to -1 for weak meteors.

Altitude Corresponding to the Maximum Magnitude

Eliminating $M_M$ from (103) (in which we take $I = I_{max}$) and from (88), we obtain:

$$\rho(z_M) \simeq \left[\frac{2^{3\mu+2}}{\mu^{\frac{\mu}{1-\mu}}}\right]^{\frac{1}{3\mu+1}} \frac{Q}{\Lambda A_o}\, \delta^{2/3}\left[\frac{\cos\zeta}{H_h}\right]^{\frac{3\mu}{3\mu+1}}\left[\frac{I_{max}}{\tau}\right]^{\frac{1}{3\mu+1}} v_o^{-\frac{6\mu+5}{3\mu+1}}\, M_o^{-\frac{2-3\mu}{3(3\mu+1)}} \qquad (108)$$

By taking $\tau = \tau_o v^P$, by retaining only the function $\rho(z_M) = f(I_{max}, v_o)$, we have:

$$\rho(z_M) \sim I_{max}^{\frac{1}{3\mu+1}}\, v_o^{-\frac{6\mu+5+p}{3\mu+1}} \qquad (109)$$

From (3), we have:

$$\log_{10}\rho_M = \log_{10}(\rho_h) + \frac{0{,}434h}{H_h} - \frac{0{,}434}{H_h} z_M = \text{const.} - \frac{0{,}434}{H_h} z_M \qquad (110)$$

From (109):

$$\log_{10}\rho_M = \text{const.} + \frac{1}{3\mu+1}\log_{10} I_{max} - \frac{6\mu+5+p}{3\mu+1}\log_{10} v_o \qquad (111)$$

$$= \text{const.} - \frac{1}{2{,}5(3\mu+1)}\mathcal{M}_{v,max} - \frac{6\mu+5+p}{3\mu+1}\log_{10} v_o$$

from which,

$$z_M = \text{const.} + \frac{H_h}{1{,}085}\,\frac{1}{3\mu+1}\mathcal{M}_{v,max} + \frac{H_h}{0{,}434}\,\frac{6\mu+5+p}{3\mu+1}\log_{10} v_o \qquad (112)$$

It is possible, for example, to use the following approximation for the atmospheric density $\rho(z)$, corresponding to $70 \le z \le 120$ km (8): $H_h$ average $= 5.8$ km ($h = 70$ km). If in addition, we take $\mu = 2/3$ (meteorite remaining similar to itself) and $p = 1$ (Whipple's approximation: $\tau = \tau_o v$), we find (Ref.8):

$$z_M = \text{const.} + 1.8\mathcal{M}_{v,max} + 44\log_{10} v_o. \qquad (113)$$

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## 12. Ionization

The ionization occurring in the vicinity of the meteorite is essentially due to collisions between the vaporized atoms and the air molecules, just as in the case of the luminous radiation. In Reference 2, a more thorough, but concise, study of this phenomenon can be found. Table 14 gives, for a few types of atoms and for different values of the speed, the proportion of atoms ionized following a collision with an oxygen molecule. Read also Sida and Öpik (Ref. 10).

### Ionization equation

We assume, as in the case of luminosity, that the necessary power for ionization is proportional to the decrease per unit time of the kinetic energy of the vaporized molecules.

$$q\ V_i\ v = -\frac{1}{2}\,\tau_q\,\frac{dM}{dt}\,v^2 \tag{114}$$

where $\tau_q$ is a dimensionless number called ionization coefficient, $q$ is number of electrons per unit length, and $V_i$ is the ionization potential.

Replacing $dM/dt$ by its value from the mass decrease equation (80), we obtain:

$$q = \frac{1}{2}\,\tau_q\,\frac{\xi\Gamma}{V_i}\,\frac{S_o}{M_o^{\mu}}\,M^{\mu}\rho v^4 = \frac{1}{2}\,\tau_q\,\frac{\xi\Gamma}{V_i}\,\frac{A_o M_o^{\frac{2}{3}-\mu}}{\delta^{2/3}}\,M^{\mu}\,\rho v^4 \tag{115}$$

### Relation between $\tau$ and $\tau_q$

From simultaneous radio and visual observations on Geminid and Perseid showers, Millmann and McKinley (Ref. 28) found that $\tau_q/\tau$ vary from 1 to 3, while $v$ varies from 35 to 60 km/sec. The following approximate relation is deduced:

$$\tau_q/\tau \sim v^2 \tag{116}$$

### Radio Magnitude of a Meteor: $\mathcal{M}_r$ (8)

One can define a scale of radio magnitudes as being related to the ionization per unit length of the meteorite train, which does not involve the visual magnitude. In fact, simultaneous radio and visual observations have led to the relation, in an empirical way, of these two types of magnitudes (Ref. 28). The radio magnitude used is the duration of the echo. An absolute duration is defined as the duration of the echo if the radar distance were 100 km.

An empirical relation, analogous to (107), is given by McKinley

$$\mathcal{M}_r \simeq 40 - 2.5 \log_{10} q, \tag{117}$$

where q is the number of electrons per meter. Equation (117) is valid for $v \simeq 40$ km/sec.

## Altitude of the Ionization Maximum

By assuming that there is constant speed, the altitude of the maxima of vaporization, luminosity, and ionization speeds are the same. From (88) and (89), (115) becomes:

$$q_{max} = \frac{1}{2} \frac{\tau_o}{V_i} \mu^{\frac{\mu}{1-\mu}} v_o^{p+4} \frac{M_o \cos\zeta}{H_h} \tag{118}$$

where we have taken,

$$\tau_q = \tau v^2 = \tau_o v^{p+2}$$

By using the same method as for the relation (113), we obtain:

$$z_M = \text{const.} + 49 \log_{10} v_o - 4.4 \log_{10} q_{max}. \tag{119}$$

Figure 18 shows the altitude $z(q_{max})$ as a function of $v = v_o$, depending on the values of $q_{max}$ or $\mathcal{M}_{r,max}$ from (117).

## 13. Conclusion

In this report, we have reviewed the successive phenomena which take place during the entry of a meteorite into the earth's atmosphere. These phenomena were described in chronological order to better explain the mechanisms involved.

When possible, we have outlined the essential characteristics of the parameters which define a meteor: altitudes corresponding to the beginning and end of the train, deceleration of the meteorite, luminosity, and ionization. These results are quite general: they can be applied to natural meteorites, as well as to artificial meteorites launched from a rocket; they are useful to all methods of meteorite observations (radio or visual); and they apply to meteorites of all dimensions, even to meteorites of dimensions greater than the millimeter or the centimeter, which are very rare.

The second part of this study has a strictly practical goal. The previous results are applied here to the case of interest of natural meteorites having usual dimensions (a few tens or a few hundred microns), and observed by radio means. We see that a simple and easily applicable description of meteors can be made in this special case.

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Translated for the National Aeronautics and Space Administration by John F. Holman and Co. Inc.

Table 1. Average Composition of a Stony Meteorite

| Element | O | Si | Mg | Fe | S | Al | Ca | Na,K |
|---|---|---|---|---|---|---|---|---|
| % in weight | 40 | 20 | 15 | 15 | 4 | 1.5 | 1.8 | <1 |
| % in number of atoms | 57 | 16-17 | 14 | 6 | 3 | 1.3 | 1 | <1 |

Table 2. Altitudes (in km) Above Which the Transparency of Reflected Air Molecules is Greater Than 0.9

| R (cm) | 10 | 1 | 0.1 | 0.01 | 0.001 | stony meteorites |
|---|---|---|---|---|---|---|
| v = 15 km/sec | 109 | 97 | 86 | 73 | 54 | |
| = 30 | 114 | 101 | 89 | 77 | 60 | |
| = 60 | 120 | 105 | 94 | 82 | 65 | |

Table 3. Altitudes (in km) Above Which the Transparency of Reflected Air Molecules is Greater Than 0.9

| R (cm) | 10 | 1 | 0.1 | 0.01 | 0.001 | iron meteors |
|---|---|---|---|---|---|---|
| z (km) | 104 | 92 | 80 | 66 | 46 | |

Table 4. $\Delta M/M_o$ Decrease of Mass by Impact Sputtering

| $\frac{\Delta v}{v_o}$ | Stony meteorites | | | Iron meteorites | | | |
|---|---|---|---|---|---|---|---|
| | $v_o = 15$ | 30 | 60 | $v_o = 15$ | 30 | 60 | |
| 0.01 | 0.003 | 0.02 | 0.12 | 0.0001 | 0.001 | 0.006 | |
| 0.1 | 0.03 | 0.17 | 0.70 | 0.001 | 0.01 | 0.06 | $v_o$ in km/sec |
| 0.28 | 0.07 | 0.37 | 0.95 | 0.003 | 0.02 | 0.13 | |
| 1 | 0.12 | 0.54 | 0.993 | 0.006 | 0.04 | 0.21 | |

Table 5. $\Delta v/v_o$ Decrease of Speed by Impact Sputtering

Vertical Trajectory; Stony Meteorite

| z \ R | 10 | 1 | 0.1 | 0.01 | 0.001 | 0.0001 | |
|---|---|---|---|---|---|---|---|
| 80 | $3 \cdot 10^{-4}$ | $3 \cdot 10^{-3}$ | $3 \cdot 10^{-2}$ | $3 \cdot 10^{-1}$ | | | |
| 100 | $2 \cdot 10^{-5}$ | $2 \cdot 10^{-4}$ | $2 \cdot 10^{-3}$ | $2 \cdot 10^{-2}$ | $2 \cdot 10^{-1}$ | | |
| 120 | $10^{-6}$ | $10^{-5}$ | $10^{-4}$ | $10^{-3}$ | $10^{-2}$ | $10^{-1}$ | R in cm |
| 140 | $6 \cdot 10^{-8}$ | $6 \cdot 10^{-7}$ | $6 \cdot 10^{-6}$ | $6 \cdot 10^{-5}$ | $6 \cdot 10^{-4}$ | $6 \cdot 10^{-3}$ | z in km |

Table 6. Temperature Decrement: $x_o$
Vertical Trajectory; Homotropous Atmosphere $H_o$ = 7 km

| $v_o$ | Stony meteorites | | Iron meteorites | |
|---|---|---|---|---|
| | Compact | Porous | | |
| 15 | 0.5 | 0.3 | 1.7 | |
| 30 | 0.4 | 0.2 | 1.2 | $v_o$ in km/sec |
| 60 | 0.3 | 0.1 | 0.9 | $x_o$ in mm |

Table 7. Values of $R_{max}$ Above Which $T_{max} < T_f$
Values of the $\rho(R_{max})$ Function Corresponding to the Altitude for Which $T_{max} = T_f$
(Stony Meteorites; Vertical Trajectory)

| $v_o$ | $R_{max}$ | $\rho(R_{max})$ | |
|---|---|---|---|
| 11.3 | 30 | $6 \cdot 10^{-9}$ | |
| 15 | 13 | $2 \cdot 10^{-9}$ | $v_o$ in km/sec |
| 30 | 2 | $3 \cdot 10^{-10}$ | $R_{max}$ in micron |
| 60 | 0.2 | $4 \cdot 10^{-11}$ | $\rho$ in g cm$^{-3}$ |

Table 8. Total Vaporization Energy Per $cm^2$ Per Sec: $QN_v m'$ as a Function of T
Energy Received by the Meteorite Per $cm^2$ Per Sec: W as a Function of T
(Vertical Trajectory; Homotropous Atmosphere $H_o = 7$ km)
(T in °K; $QN_v m'$ and W in $erg \cdot cm^{-2} s^{-1}$; $v_o$ in km/sec)

| T | $QN_v m'$ | Iron meteorites | | | Compact stony meteorites | | | Porous stony meteorites | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | $W(x10^{10})$ | | | $W(x10^{10})$ | | | $W(x10^{9})$ | | |
| | | $v_o = 15$ | 30 | 60 | 15 | 30 | 60 | 15 | 30 | 60 |
| 1800 | $3 \cdot 10^7$ | | | | | | | 1.1 | 1.6 | 2.2 |
| 1900 | $10^8$ | | | | | | | 1.2 | 1.7 | 2.4 |
| 2000 | $4 \cdot 10^8$ | 3.0 | 4.3 | 6.0 | 0.9 | 1.3 | 1.9 | 1.3 | 1.8 | 2.5 |
| 2100 | $10^9$ | 3.2 | 4.5 | 6.4 | 1.0 | 1.4 | 2.0 | 1.3 | 1.9 | 2.7 |
| 2200 | $3 \cdot 10^9$ | 3.4 | 4.8 | 6.7 | 1.0 | 1.5 | 2.1 | 1.4 | 2.0 | 2.8 |
| 2300 | $9 \cdot 10^9$ | 3.5 | 5.0 | 7.1 | 1.1 | 1.6 | 2.2 | 1.5 | 2.1 | 3.0 |
| 2400 | $2 \cdot 10^{10}$ | 3.7 | 5.3 | 7.4 | 1.2 | 1.6 | 2.3 | 1.6 | 2.2 | 3.1 |
| 2500 | $5 \cdot 10^{10}$ | 3.9 | 5.5 | 7.8 | 1.2 | 1.7 | 2.4 | | | |
| 2600 | $10^{11}$ | 4.1 | 5.8 | 8.2 | 1.3 | 1.8 | 2.5 | | | |

Table 9. Theoretical Average Altitude at the Beginning of Visibility (Vertical Trajectory; Homotropous Atmosphere $h_o = 7$ km)

| | $v_o = 15$ | 30 | 60 | |
|---|---|---|---|---|
| iron meteorites | 74 | 86 | 98 | |
| compact stony meteorites | 82 | 94 | 106 | z in km |
| porous stony meteorites | 96 | 108 | 120 | $v_o$ in km/sec |

Table 10. Transparency Coefficient of Vaporized Molecules

| | $\alpha$ | | |
|---|---|---|---|
| $\rho v^3$ | R = 0.1 | R = 1 | |
| $3 \cdot 10^{10}$ | 0.35 | 0.08 | |
| $10^{11}$ | 0.18 | 0.03 | $\rho$ in g $cm^{-3}$ |
| $3 \cdot 10^{11}$ | 0.08 | 0.01 | v in km/sec |
| $10^{12}$ | 0.03 | 0.005 | R in cm |

Table 11. Values of $M(0)/M_o$ as a Function of $v_o$

| $v_o$ | $\xi = 2 \cdot 10^{-12}$ | $\xi = 10^{-12}$ |
|---|---|---|
| 15 | 0.1 | 0.3 |
| 30 | $10^{-4}$ | 0.01 |
| 60 | $10^{-16}$ | $2 \cdot 10^{-8}$ |

Table 12. Dissociation and Ionization Energies (in ev)

| | $N_2$ | N | $N_2^+$ | $O_2$ | O | $O_2^+$ | $H_2$ | H | $H_2^+$ | A | Na | NO |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| dissociat. | 9.75 | | 8.7 | 5 | | 6.5 | 4.5 | | 2.7 | | | 6.5 |
| ionizat. | 15.6 | 14.5 | | 12.2 | 13.5 | | 15.4 | 13.6 | | 15.8 | 5.1 | 9.5 |

1 ev = $1.6 \cdot 10^{-12}$ erg

Table 13. Rate of Molecular Dissociation: f
Luminosity Coefficient for Impact Radiation: $\tau_1$

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| v | 5.2 | 7.4 | 10.4 | 14.8 | 20.9 | 29.6 | 41.8 | 59.2 | km/sec |
| f | 0 | 0 | 1/8 | 1/2 | 1 | 1 | 1 | 1 | |
| | 0 | $1.7\cdot10^{-4}$ | 7.1 | 10 | 9.6 | 6.4 | 4.5 | 3.7 | very diluted coma |
| $\tau_1$ | 0 | $0.4\cdot10^{-4}$ | 5.3 | 11 | 14.6 | 16.7 | 21 | 26 | dense coma |

Table 14. Ionized Atoms by Collisions with Air Molecules

| v | 14.8 | 20.9 | 29.6 | 41.8 | 59.2 | 83.6 | $v_{min}$ |
|---|---|---|---|---|---|---|---|
| $n(Fe^+)$ | $2.5\cdot10^7$ | $12\cdot10^7$ | $17.4\cdot10^7$ | $16.4\cdot10^7$ | $12.7\cdot10^7$ | $9.1\cdot10^7$ | 11.6 |
| $\nu(Fe^+)$ | 0.0025 | 0.024 | 0.07 | 0.13 | 0.21 | 0.30 | |
| $n(O_2^+)$ | 0 | $10^7$ | $9.2\cdot10^7$ | $23.5\cdot10^7$ | $39.8\cdot10^7$ | $56.8\cdot10^7$ | 17.0 |
| $n(Mg^+)$ | $1.4\cdot10^7$ | $10.9\cdot10^7$ | $20.7\cdot10^7$ | $22\cdot10^7$ | $17.8\cdot10^7$ | $13\cdot10^7$ | 13 |
| $\nu(Mg^+)$ | 0.0006 | 0.009 | 0.0 3 | 0.0 7 | 0.11 | 0.15 | |
| $n(O_2^+)$ | 0 | $0.1\cdot10^7$ | $5.8\cdot10^7$ | $19.2\cdot10^7$ | $34.9\cdot10^7$ | $52\cdot10^7$ | 20 |
| $n(Si^+)$ | $1.8\cdot10^7$ | $11.2\cdot10^7$ | $20.2\cdot10^7$ | $20.7\cdot10^7$ | $16.4\cdot10^7$ | $12.1\cdot10^7$ | 12.7 |
| $\nu(Si^+)$ | 0.0009 | 0.01 | 0.04 | 0.08 | 0.12 | 0.16 | |
| $n(O_2^+)$ | 0 | $0.2\cdot10^7$ | $6.5\cdot10^7$ | $20\cdot10^7$ | $35.8\cdot10^7$ | $52.9\cdot10^7$ | 19.4 |
| $n(O_2^+)$ | 0 | $1.6\cdot10^7$ | $9\cdot10^7$ | $20.5\cdot10^7$ | $37\cdot10^7$ | $53.3\cdot10^7$ | 20 |

Additional explanations for Table 14
v: initial speed (in km/sec)

$v_{min}$: Minimum of initial speed which is necessary to create ionization (in km/sec)

$N(\mathcal{E}^+)$: Number of ions of element $\mathcal{E}$, per erg of initial energy

$\nu(\mathcal{E}^+) = \dfrac{n(\mathcal{E}^+)}{n(\mathcal{E} \neq \mathcal{E}^+)}$ : Rate of ionization of $\mathcal{E}$ element

$n(O_2^+)$: Number of $O^+$ ions created by collisions with atoms of $\mathcal{E}$ element, per erg

## GLOSSARY

| | |
|---|---|
| $S$ | Right-angle cross section of the meteorite |
| $R$ | Radius of the right-angle cross section |
| $S'$ | Convex envelope of the meteorite |
| $v$ | Speed of the meteorite |
| $v_o$ | Initial speed of the meteorite |
| $v_1$ | Speed at the beginning of the meteorite vaporization |
| $v_2$ | Speed at the end of the meteorite visibility |
| $v_r$ | Speed[1] of reflected air molecules |
| $v_T$ | Speed[1] of molecules vaporized from the meteorite |
| $v_a$ | Speed[1] of the molecules stripped from the meteorite |
| $M$ | Mass of the meteorite |
| $\delta$ | Density of the meteorite |
| $V$ | Volume of the meteorite |
| $\Lambda, \Lambda_a$ | Energy transfer coefficient |
| $\Gamma$ | Drag coefficient |
| $\alpha$ | Transparency coefficient |
| $Q$ | Overall specific energy of heating and vaporization |
| $a$ | Accommodation coefficent |
| $A$ | Shape factor of the meteorite |
| $\kappa$ | Coefficient of thermal conductivity |
| $\chi$ | Coefficient of thermometric conductivity |
| $\varepsilon$ | Molecular energy of impact |

---

[1]Root mean square speeds.

| | |
|---|---|
| $u_o$ | Energy of stripping of an atom |
| $d$ | Mean molecular diameter |
| $m$ | Mean molecular mass |
| $\mathcal{M}$ | Mean molar mass of air |
| $\rho$ | Specific mass of air |
| $H$ | Referential height of the atmosphere |
| $\lambda_o$, $\lambda$ | Mean free path |
| $\zeta$ | Zenith of the meteor radiant |
| $z$ | Altitude |
| $T$, $\theta$ | Temperature |
| $T_o$ | Temperature of the meteorite before entry into the dense atmosphere |

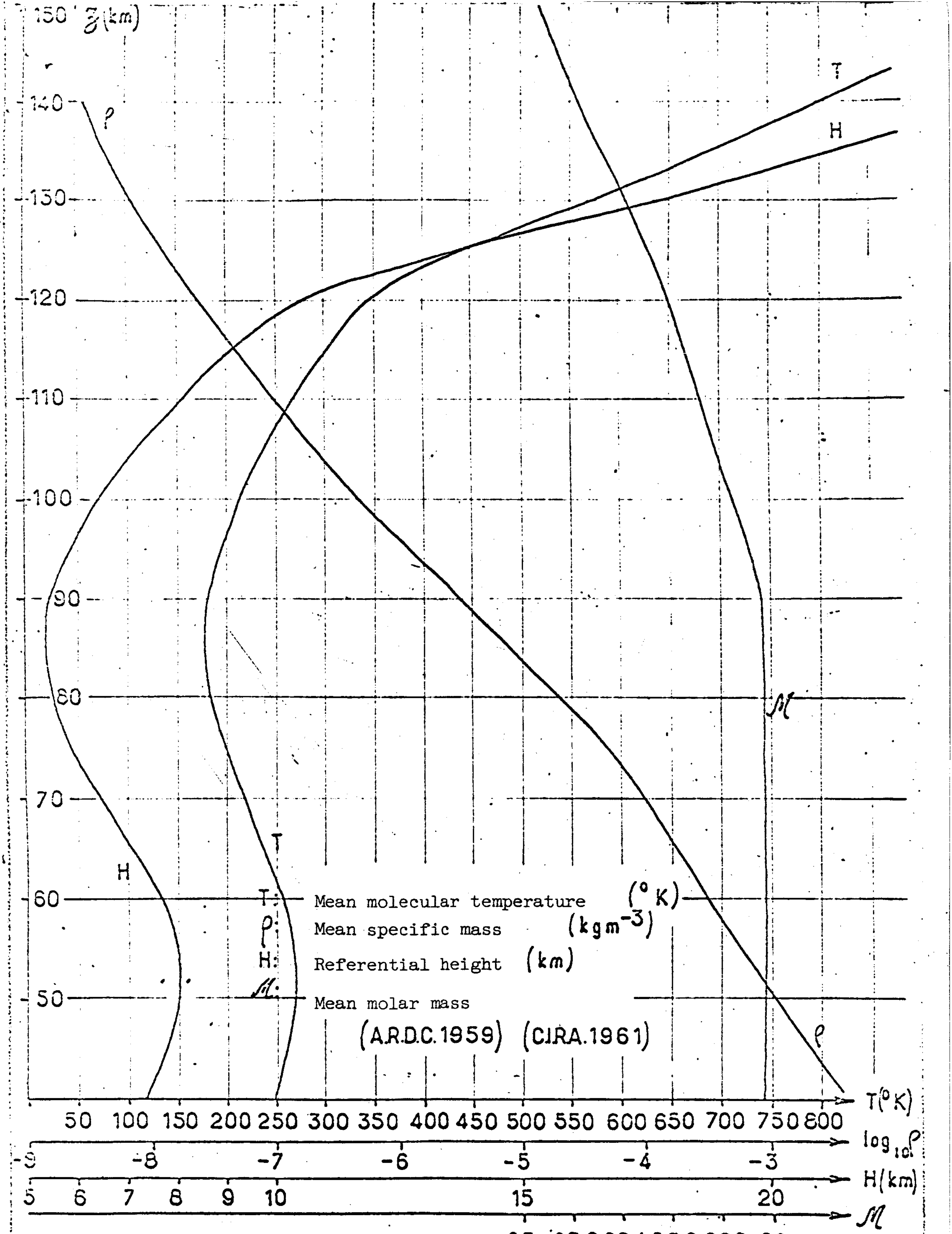
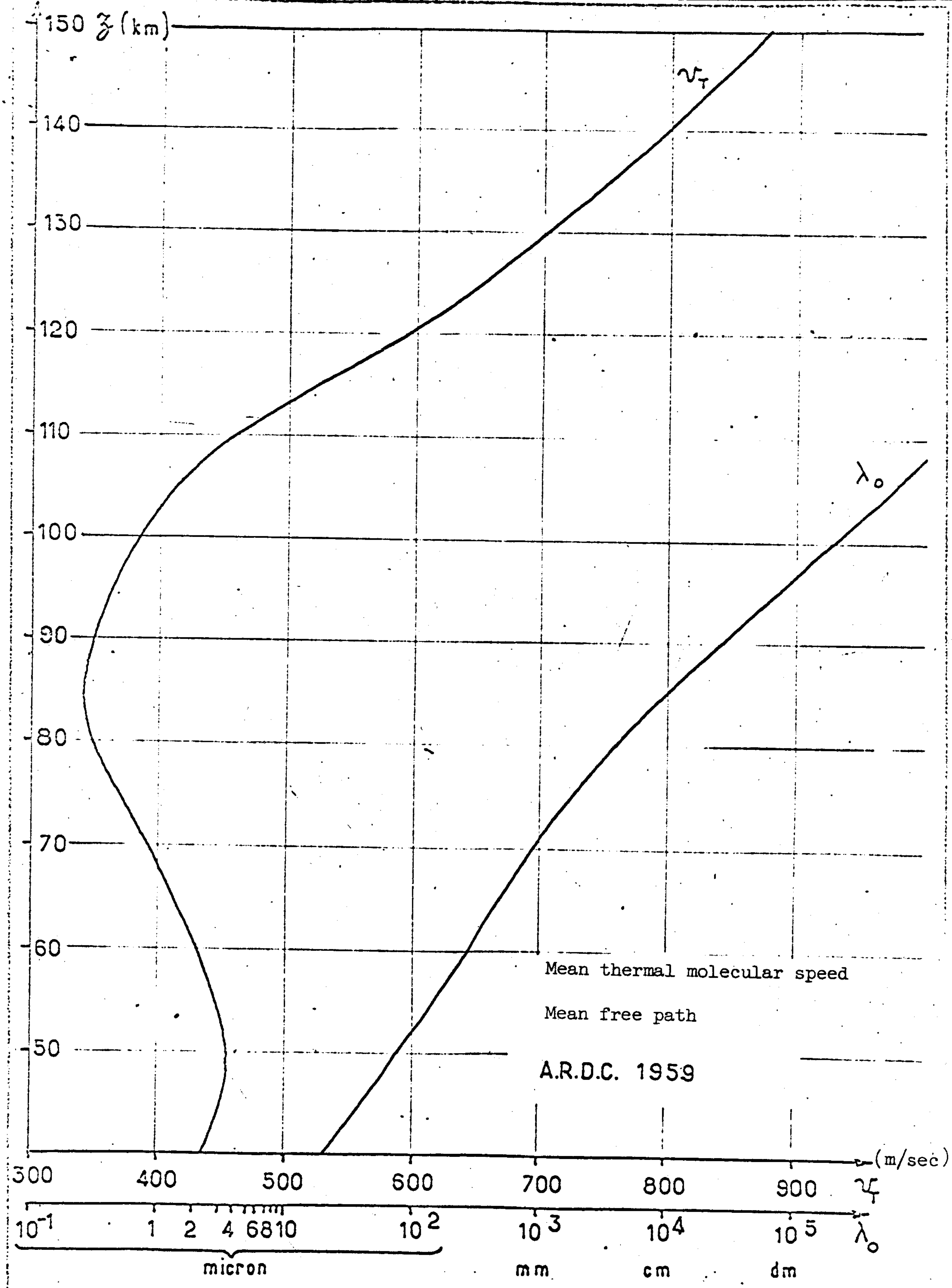

Z(km)
T
H
ρ
T
H
ρ
M
T: Mean molecular temperature (°K)
ρ: Mean specific mass (kgm$^{-3}$)
H: Referential height (km)
M: Mean molar mass
(A.R.D.C.1959) (C.I.R.A.1961)
T(°K)
log$_{10}$ρ
H(km)
M

Figure 1.



150 z (km)
140
130
120
110
100
90
80
70
60
50
$v_T$
$\lambda_o$
Mean thermal molecular speed
Mean free path
A.R.D.C. 1959
300 400 500 600 700 800 900 (m/sec) $v_T$
$10^{-1}$ 1 2 4 6 8 10 $10^2$ $10^3$ $10^4$ $10^5$ $\lambda_o$
micron
mm
cm
dm


Figure 2.

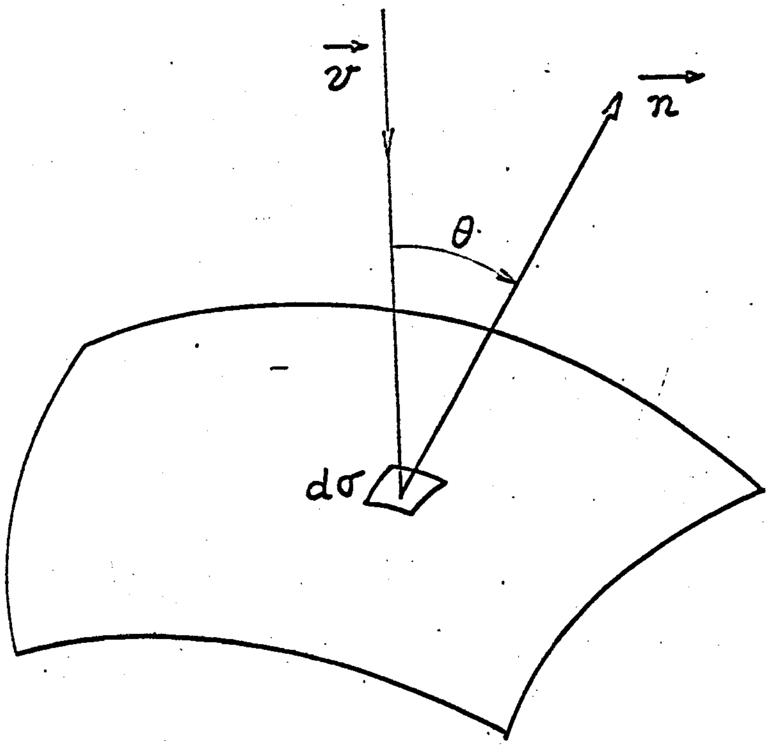



Figure 3.

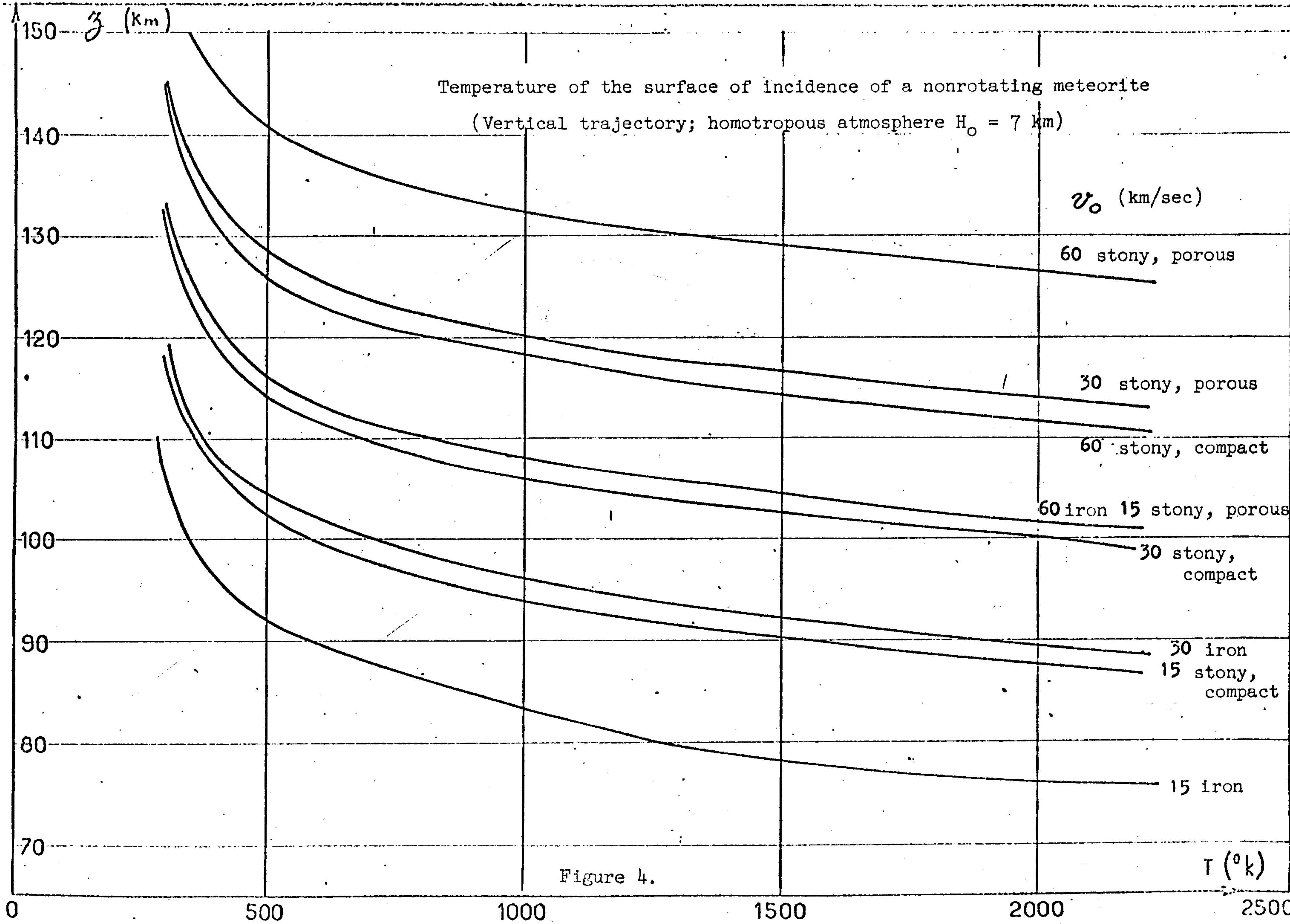

Temperature of the surface of incidence of a nonrotating meteorite
(Vertical trajectory; homotropous atmosphere $H_o$ = 7 km)
$v_o$ (km/sec)
60 stony, porous
30 stony, porous
60 stony, compact
60 iron 15 stony, porous
30 stony, compact
30 iron
15 stony, compact
15 iron
$z$ (km)
150
140
130
120
110
100
90
80
70
0
500
1000
1500
2000
2500
T (°k)

Figure 4.

Temperature of a spherical stony micrometeorite (before vaporization)
(Vertical trajectory; homotropous atmosphere $H_o = 7$ km)

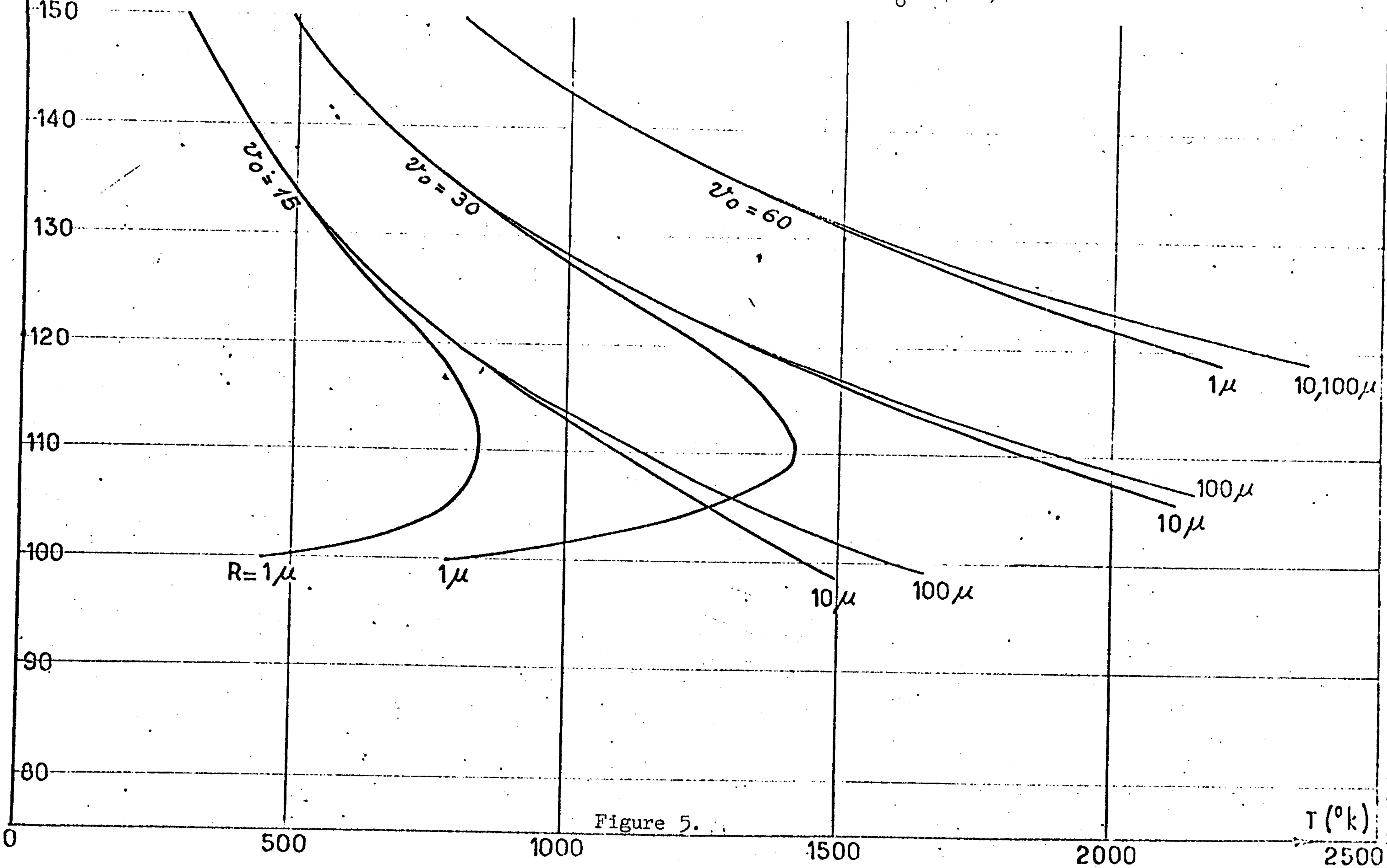



Figure 5.

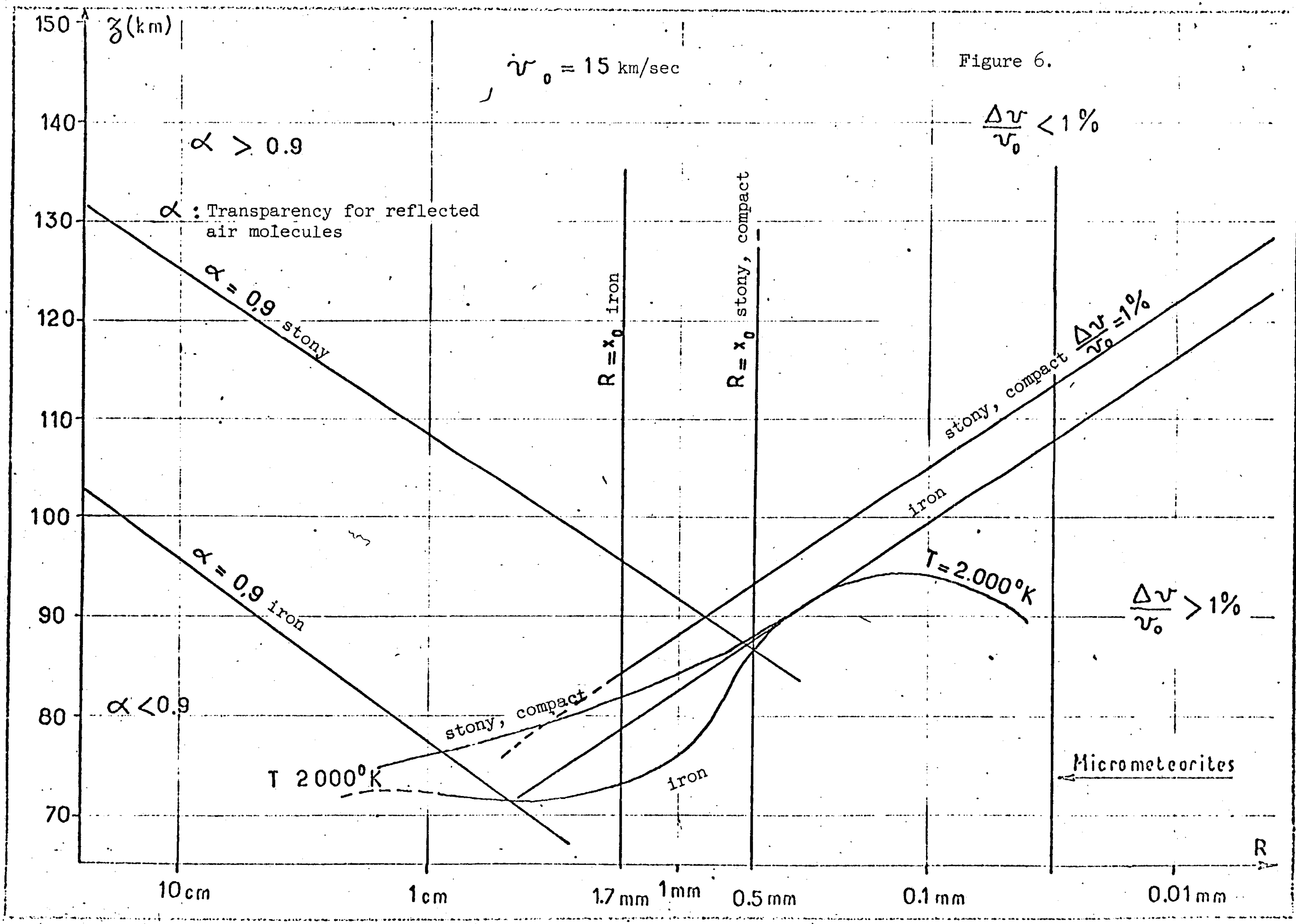
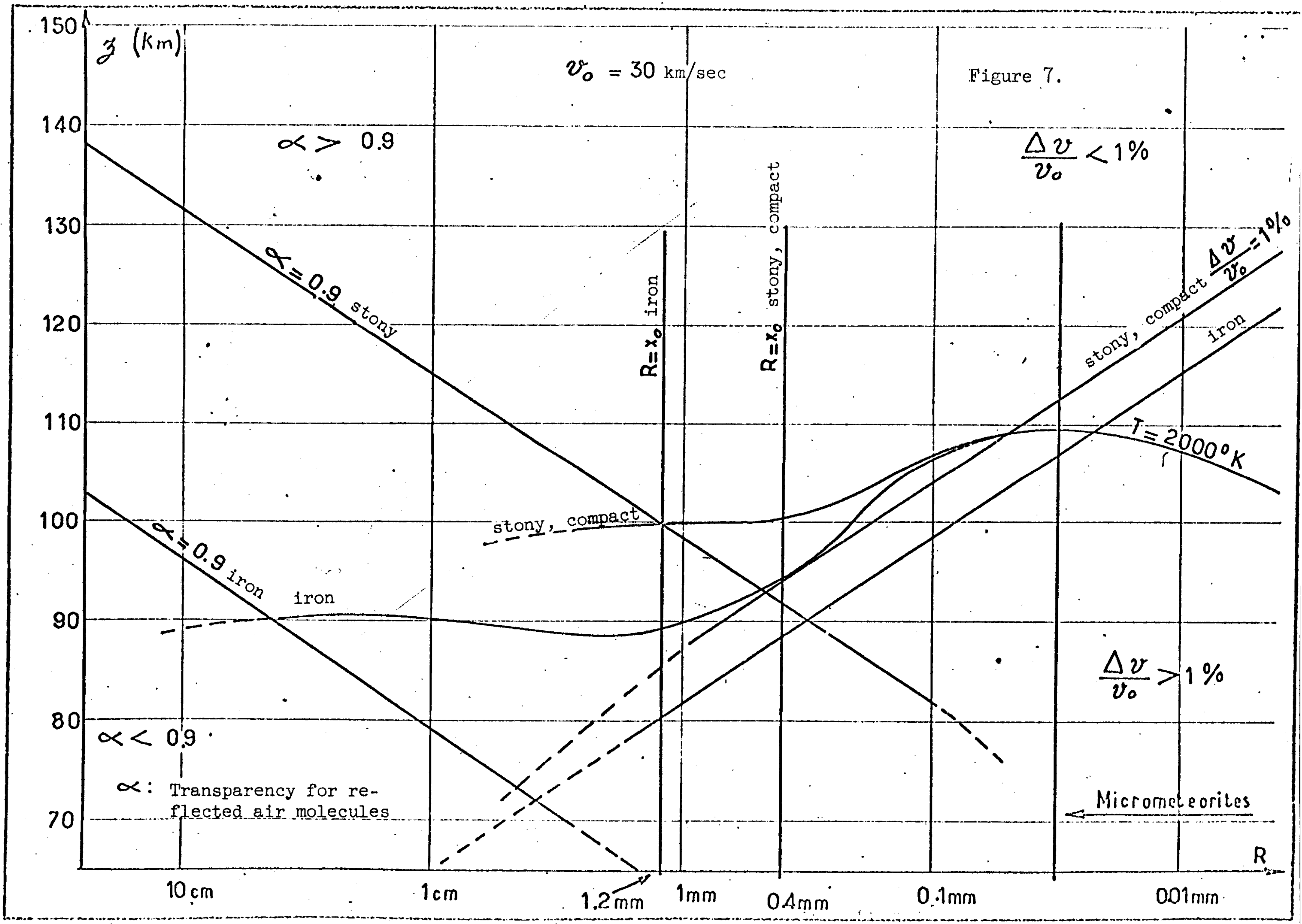

$\dot{v}_0 = 15$ km/sec
$\frac{\Delta v}{v_0} < 1\%$
$\alpha > 0.9$
$\alpha$ : Transparency for reflected air molecules
$\alpha = 0,9$ stony
$\alpha = 0,9$ iron
$\alpha < 0.9$
$R = x_0$ iron
$R = x_0$ stony, compact
stony, compact $\frac{\Delta v}{v_0} = 1\%$
iron
$T = 2.000°K$
$\frac{\Delta v}{v_0} > 1\%$
stony, compact
iron
T 2000°K
Micrometeorites
z (km)
R
10 cm
1 cm
1.7 mm
1 mm
0.5 mm
0.1 mm
0.01 mm

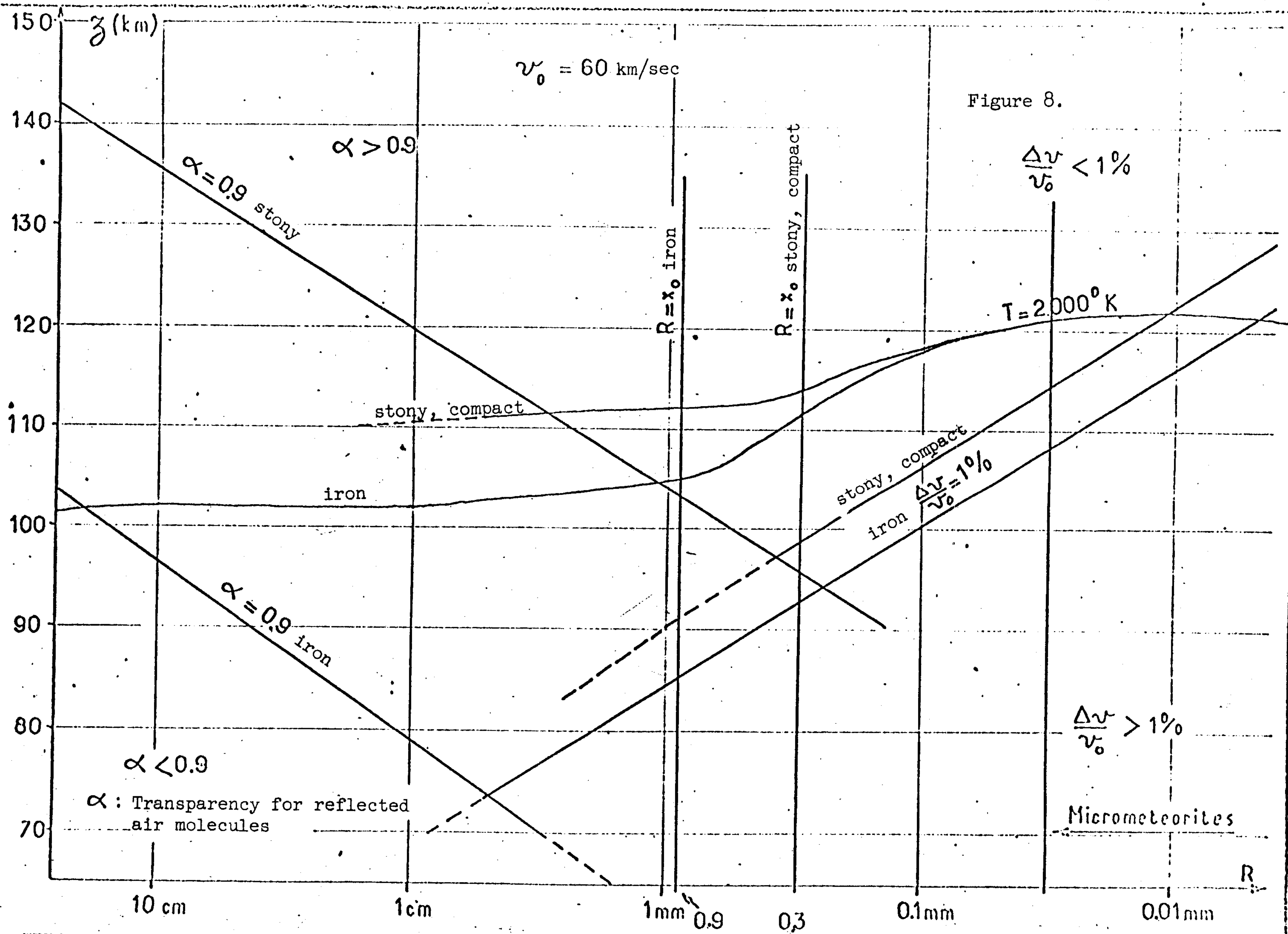
Figure 6.



$z$ (Km)
150
140
130
120
110
100
90
80
70
$v_o$ = 30 km/sec
$\alpha > 0.9$
$\alpha < 0.9$
$\alpha$ = 0.9 stony
$\alpha$ = 0.9 iron
iron
stony, compact
R=$x_o$ iron
R=$x_o$ stony, compact
stony, compact $\frac{\Delta v}{v_o} = 1\%$
iron
T=2000°K
$\frac{\Delta v}{v_o} < 1\%$
$\frac{\Delta v}{v_o} > 1\%$
Micrometeorites
$\alpha$: Transparency for reflected air molecules
R
10 cm
1 cm
1.2 mm
1mm
0.4mm
0.1mm
0.01mm

Figure 7.

Figure 8.



z (km)
150
140
130
120
110
100
90
80
70
$v_0$ = 60 km/sec
$\alpha > 0.9$
$\alpha = 0.9$ stony
$\alpha = 0.9$ iron
$\alpha < 0.9$
$\alpha$ : Transparency for reflected air molecules
stony, compact
iron
$R = x_0$ iron
$R = x_0$ stony, compact
$T = 2.000^0$ K
$\frac{\Delta v}{v_0} < 1\%$
$\frac{\Delta v}{v_0} > 1\%$
stony, compact
iron $\frac{\Delta v}{v_0} = 1\%$
Micrometeorites
R
10 cm
1 cm
1 mm
0.9
0.3
0.1 mm
0.01 mm

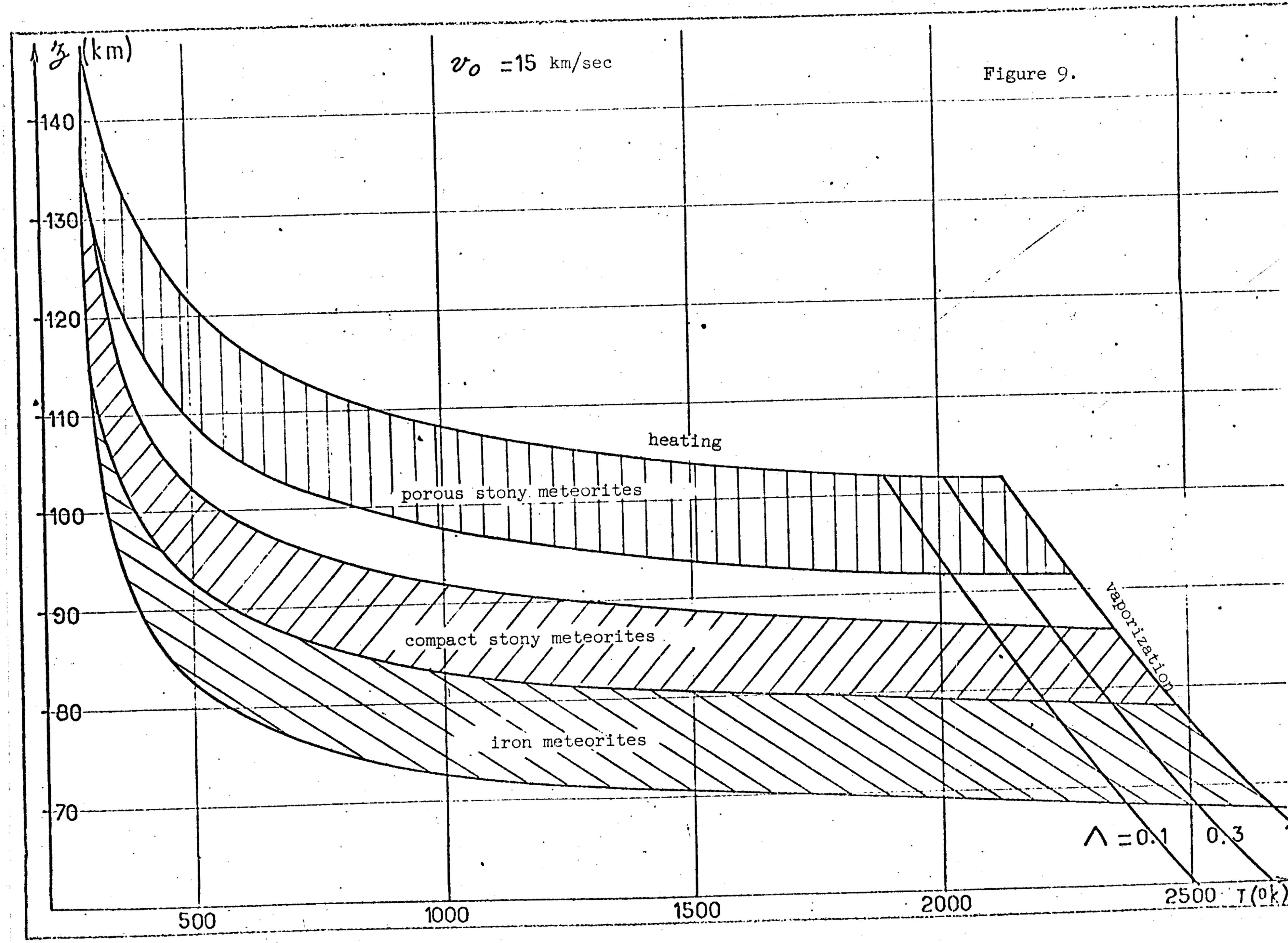

z (km)
140
130
120
110
100
90
80
70
$v_0$ =15 km/sec
heating
porous stony meteorites
compact stony meteorites
iron meteorites
vaporization
$\Lambda$ = 0.1
0.3
1
500
1000
1500
2000
2500
T (°K)

Figure 9.

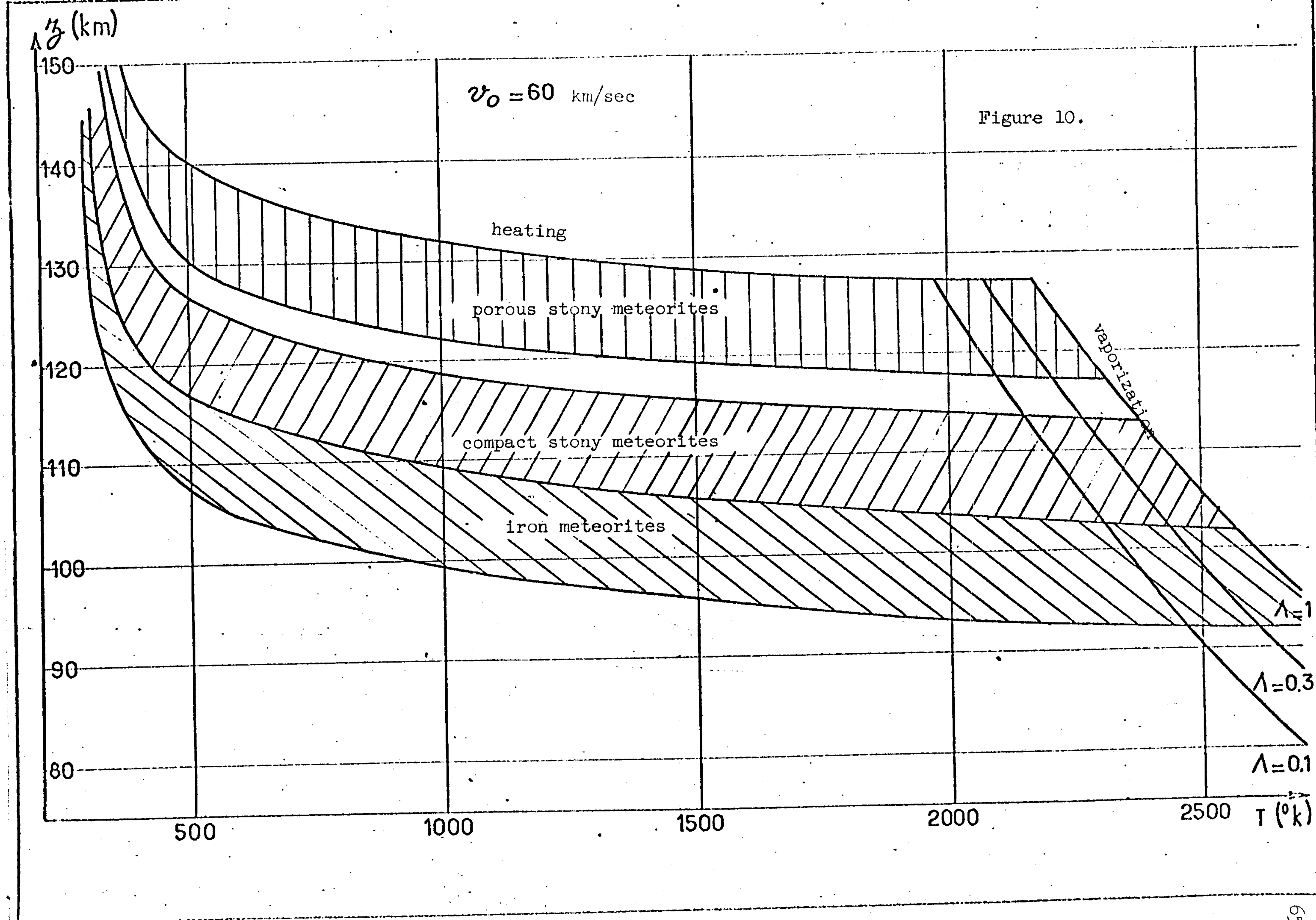

z (km)
150
140
130
120
110
100
90
80
500
1000
1500
2000
2500
T (°k)
$v_0$ = 60 km/sec
heating
porous stony meteorites
compact stony meteorites
iron meteorites
vaporization
Λ=1
Λ=0.3
Λ=0.1

Figure 10.

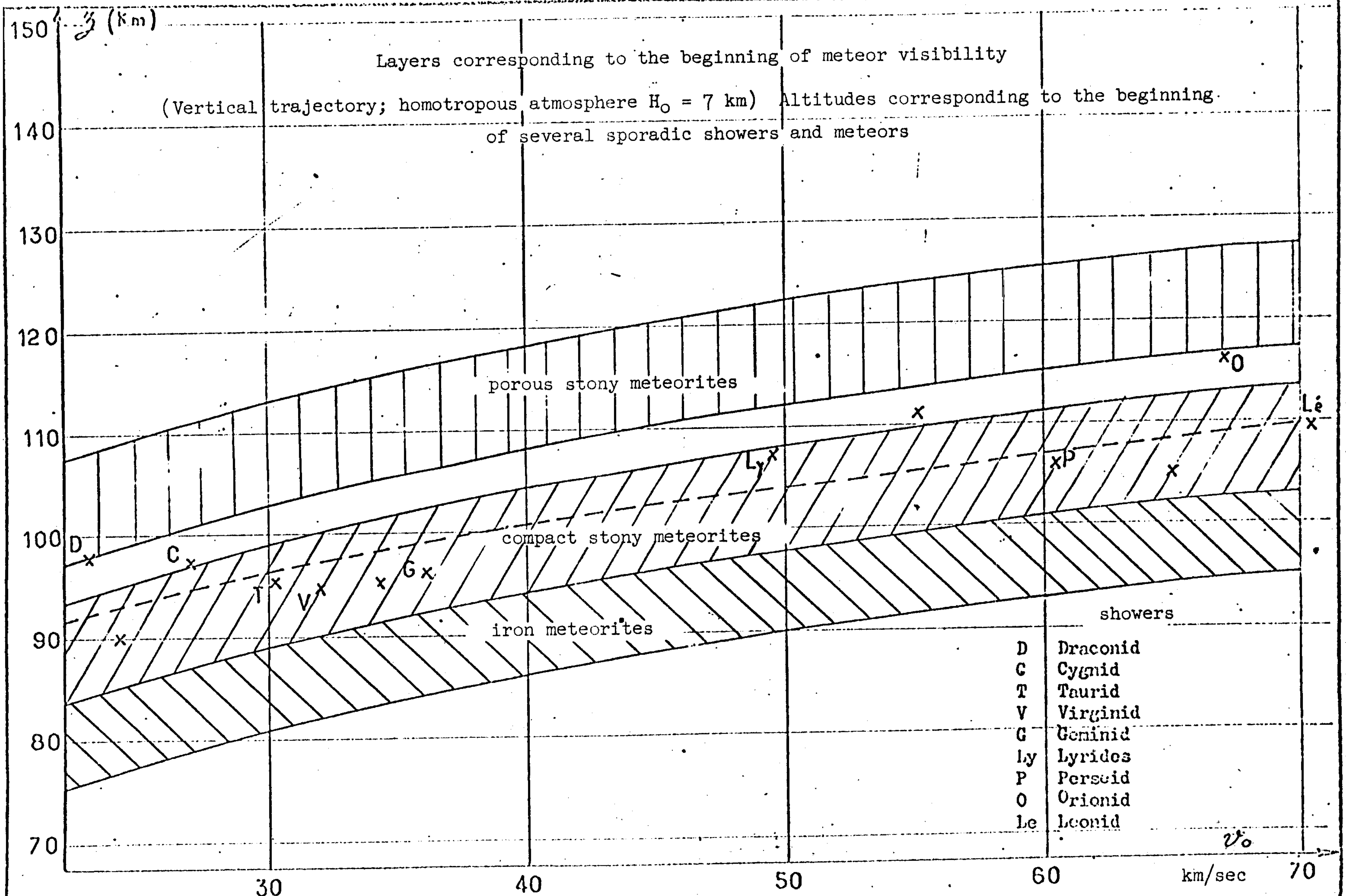
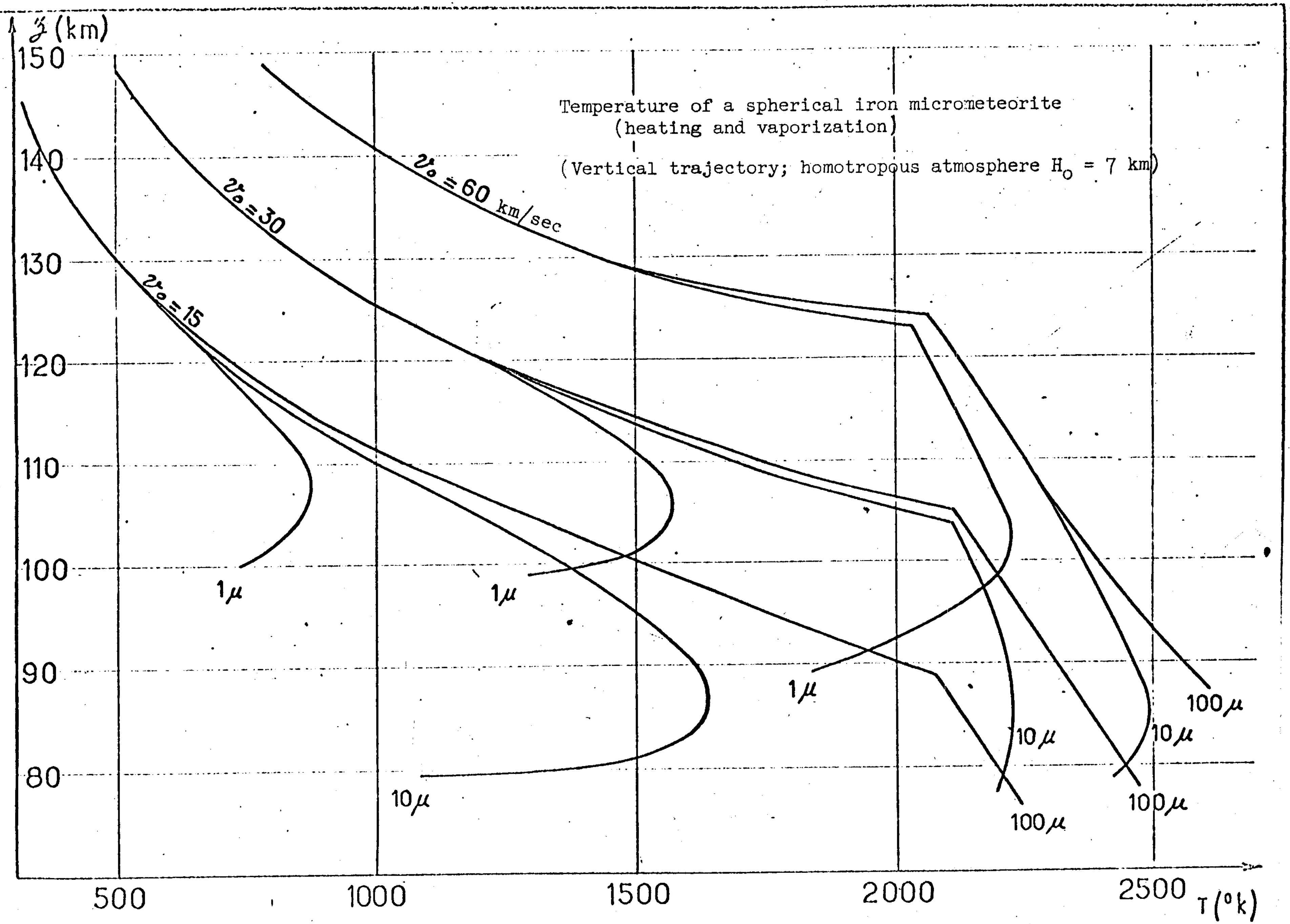
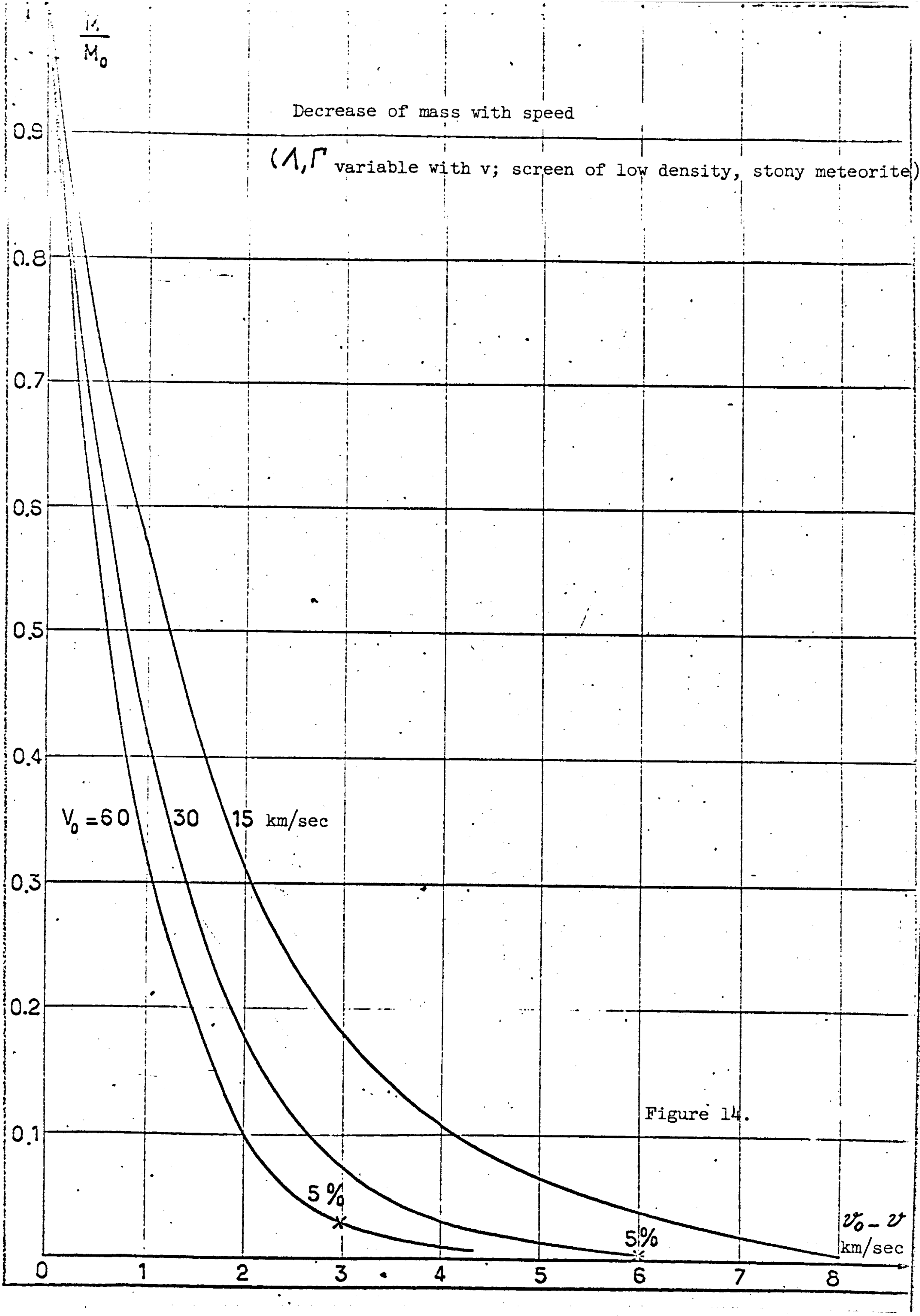

Layers corresponding to the beginning of meteor visibility
(Vertical trajectory; homotropous atmosphere $H_o$ = 7 km)
Altitudes corresponding to the beginning of several sporadic showers and meteors
$z$ (km)
150
140
130
120
110
100
90
80
70
30
40
50
60
70
km/sec
$v_o$
porous stony meteorites
compact stony meteorites
iron meteorites
D
C
T
V
G
Ly
P
O
Le
showers
D Draconid
C Cygnid
T Taurid
V Virginid
G Geminid
Ly Lyrides
P Perseid
O Orionid
Le Leonid

Figure 11.



Temperature of a spherical iron micrometeorite
(heating and vaporization)
(Vertical trajectory; homotropous atmosphere $H_o$ = 7 km)
$\mathfrak{z}$ (km)
150
140
130
120
110
100
90
80
500
1000
1500
2000
2500
T (°k)
$v_o$ = 60 km/sec
$v_o$ = 30
$v_o$ = 15
1μ
1μ
1μ
10μ
10μ
10μ
10μ
100μ
100μ
100μ
100μ


Figure 12.



$\frac{M}{M_0}$
Decrease of mass with speed
($\Lambda$, $\Gamma$ variable with v; screen of low density, stony meteorite)
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
$V_0$ = 60 30 15 km/sec
5 %
5%
$v_0 - v$
km/sec
0
1
2
3
4
5
6
7
8


Figure 14.

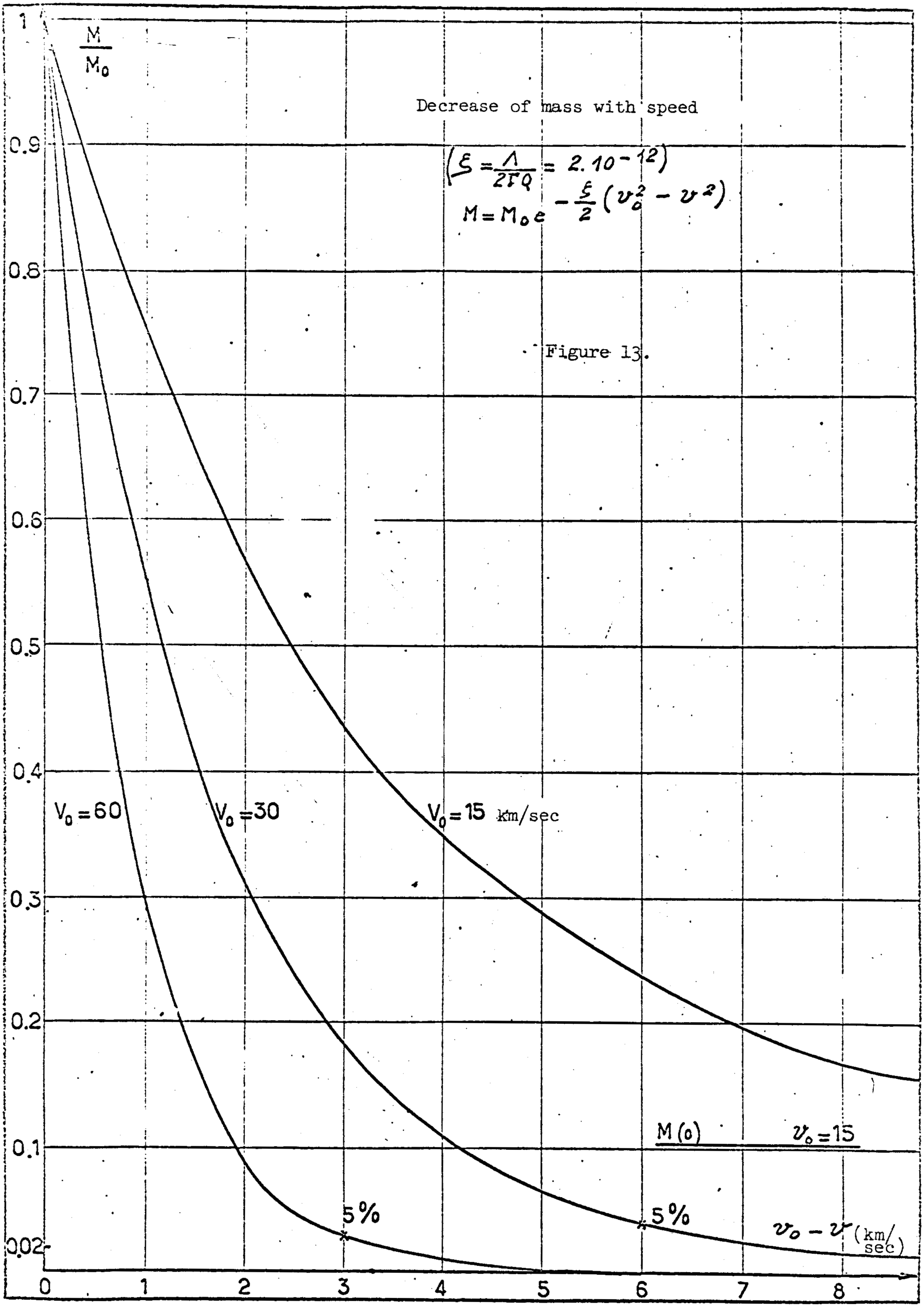
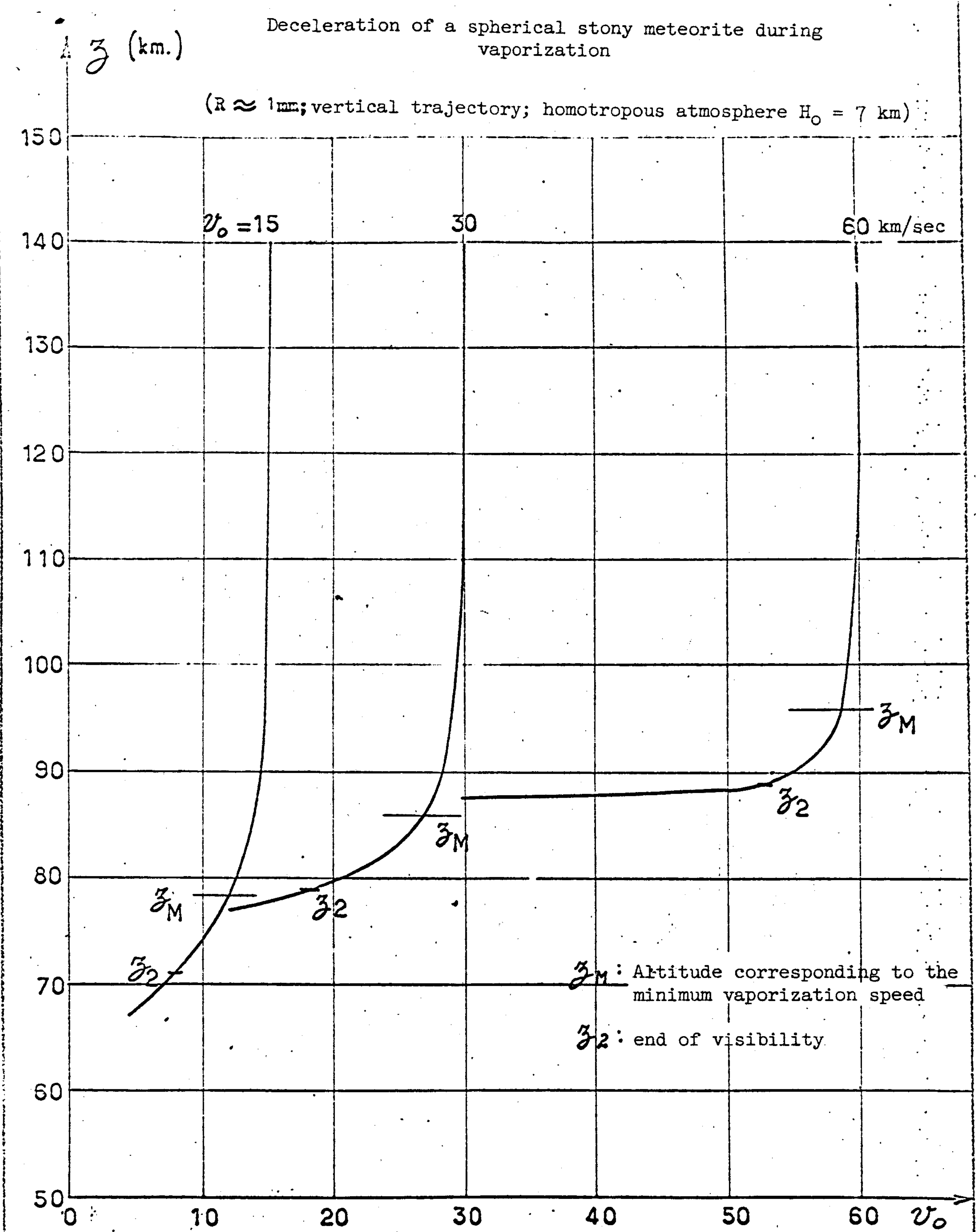
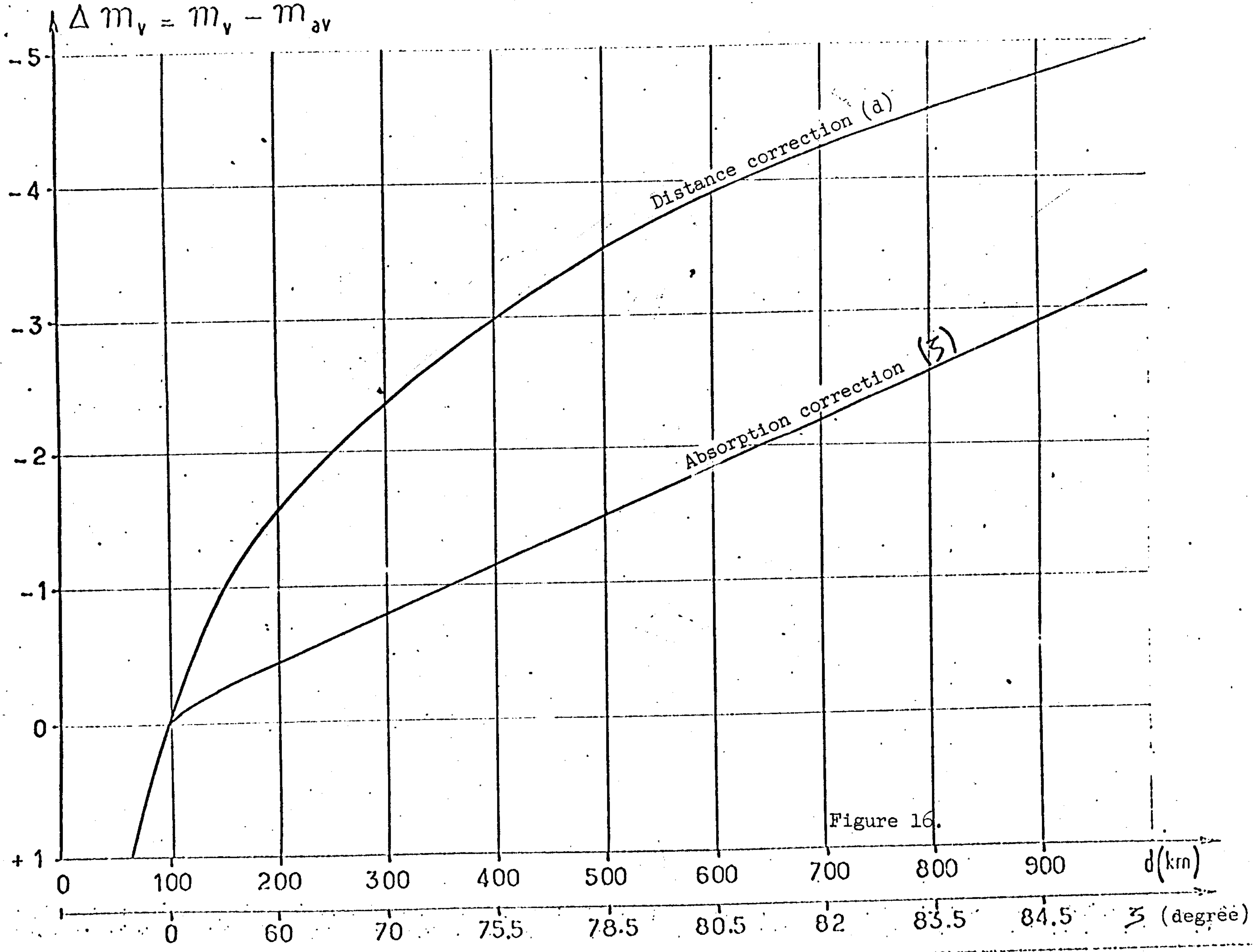

$\frac{M}{M_0}$
Decrease of mass with speed
$\left(\xi = \frac{\Lambda}{2\Gamma Q} = 2.10^{-12}\right)$
$M = M_0 e^{-\frac{\xi}{2}(v_0^2 - v^2)}$
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.02
$V_0 = 60$
$V_0 = 30$
$V_0 = 15$ km/sec
M (o)
$v_0 = 15$
5 %
5 %
$v_0 - v$ (km/sec)
0
1
2
3
4
5
6
7
8

Figure 13.



Deceleration of a spherical stony meteorite during vaporization
(R ≈ 1mm; vertical trajectory; homotropous atmosphere $H_o$ = 7 km)
z (km.)
150
140
130
120
110
100
90
80
70
60
50
$v_o$ =15
30
60 km/sec
$z_M$
$z_2$
0
10
20
30
40
50
60
$v_o$
(km/sec)
$z_M$ : Altitude corresponding to the minimum vaporization speed
$z_2$ : end of visibility


Figure 15.



Δ m_v = m_v − m_av
-5
-4
-3
-2
-1
0
+1
Distance correction (d)
Absorption correction (ζ)
0
100
200
300
400
500
600
700
800
900
d(km)
0
60
70
75.5
78.5
80.5
82
83.5
84.5
ζ (degrée)


Figure 16.

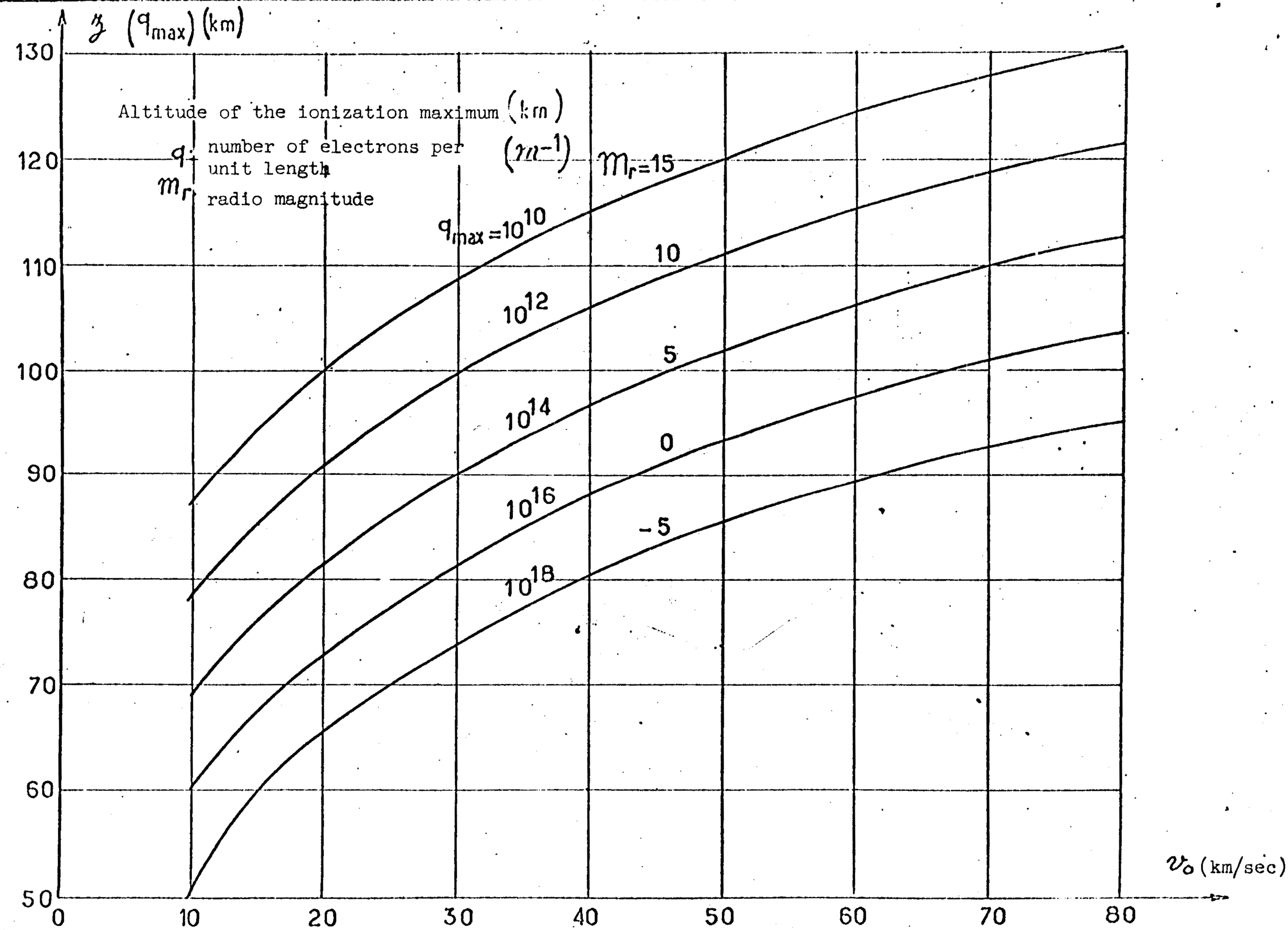

$z$ $(q_{max})$ (km)
Altitude of the ionization maximum (km)
$q$: number of electrons per unit length ($m^{-1}$)
$m_r$: radio magnitude
$m_r$=15
10
5
0
-5
$q_{max}=10^{10}$
$10^{12}$
$10^{14}$
$10^{16}$
$10^{18}$
130
120
110
100
90
80
70
60
50
0
10
20
30
40
50
60
70
80
$v_0$ (km/sec)

Figure 17

PHYSICS OF METEORS


SUMMARY

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The present report reviews various papers on the physical theory of meteors, and attempts to synthesize them for applications to radio meteors.


## Introduction

The physical theory of meteors involves the description and analysis of the phenomena which take place both inside of and in the neighborhood of a meteorite during its path through the atmosphere. The present study is presented in two parts:

(1) A fairly general report of the processes which lead to the formation of a luminous or ionized track; and

(2) A note which concerns more particularly radio meteorites, and which leads to a few relations which are necessary for practical applications.

In this first report, the phenomena are studied in the order by which they naturally occur: heating, melting and vaporization, and luminosity and ionization. From the macroscopic standpoint, most of the parameters which are involved in the explanation of the phenomena were retained in the formulas. Simplifying hypotheses have then made it possible to reduce the number of these parameters to obtain directly usable relations. These form the topic of the previously mentioned second part.

This applies to a body which does not break up in flight. A few observations of luminous meteors do not seem to support, however, the hypothesis of a meteorite remaining compact during its trajectory. In this case, we are led to assume that the meteorite has a structure which is easily pulverized, and that indeed it does break up into many particles. The mean density of these agglomerations is not known with precision. We shall assume that these reservations do not apply to radio meteors.

## 1. Hypothesis on the Meteorite

To explain quantitatively the physics of meteors, it is necessary to advance certain hypotheses on the geometrical shape of the meteorite. We have available only very little information on this subject. However, for